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Simulation of a Proposed Emergency Outlet from Devils Lake, North Dakota

Water-Resources Investigations Report 02-4042

U.S. Department of the Interior
U.S. Geological Survey

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By Aldo V. Vecchia

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Bismarck, North Dakota
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By Aldo V. Vecchia

Abstract

From 1993 to 2001, Devils Lake rose more than 25 feet, flooding farmland, roads, and structures around the lake and causing more than $400 million in damages in the Devils Lake Basin. In July 2001, the level of Devils Lake was at 1,448.0 feet above sea level[1], which was the highest lake level in more than 160 years. The lake could continue to rise to several feet above its natural spill elevation to the Sheyenne River (1,459 feet above sea level) in future years, causing extensive additional flooding in the basin and, in the event of an uncontrolled natural spill, downstream in the Red River of the North Basin as well. The outlet simulation model described in this report was developed to determine the potential effects of various outlet alternatives on the future lake levels and water quality of Devils Lake.

Lake levels of Devils Lake are controlled largely by precipitation on the lake surface, evaporation from the lake surface, and surface inflow. For this study, a monthly water-balance model was developed to compute the change in total volume of Devils Lake, and a regression model was used to estimate monthly water-balance data on the basis of limited recorded data. Estimated coefficients for the regression model indicated fitted precipitation on the lake surface was greater than measured precipitation in most months, fitted evaporation from the lake surface was less than estimated evaporation in most months, and ungaged inflow was about 2 percent of gaged inflow in most months.

Dissolved sulfate was considered to be the key water-quality constituent for evaluating the effects of a proposed outlet on downstream water quality. Because large differences in sulfate concentrations existed among the various bays of Devils Lake, monthly water-balance data were used to develop detailed water and sulfate mass-balance models to compute changes in sulfate load for each of six major storage compartments in response to precipitation, evaporation, inflow, and outflow from each compartment. The storage compartments--five for Devils Lake and one for Stump Lake--were connected by bridge openings, culverts, or natural channels that restricted mixing between compartments. A numerical algorithm was developed to calculate inflow and outflow from each compartment.

Sulfate loads for the storage compartments first were calculated using the assumptions that no interaction occurred between the bottom sediments and the water column and no wind- or buoyancy-induced mixing occurred between compartments. However, because the fitted sulfate loads did not agree with the estimated sulfate loads, which were obtained from recorded sulfate concentrations, components were added to the sulfate mass-balance model to account for the flux of sulfate between bottom sediments and the lake and for mixing between storage compartments. Mixing between compartments can occur during periods of open water because of wind and during periods of ice cover because of water-density differences between compartments. Sulfate loads calculated using the sulfate mass-balance model with sediment interaction and mixing between compartments closely matched sulfate loads computed from historical concentrations.

The water and sulfate mass-balance models were used to calculate potential future lake levels and sulfate concentrations for Devils Lake and Stump Lake given potential future values of monthly precipitation,

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[1]In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

evaporation, and inflow. Potential future inputs were generated using a scenario approach and a stochastic approach. In the scenario approach, historical values of precipitation, evaporation, and inflow were repeated in the future for a particular sequence of historical years. In the stochastic approach, a statistical time-series model was developed to randomly generate potential future inputs. The scenario approach was used to evaluate the effectiveness of various outlet alternatives, and the stochastic approach was used to evaluate the hydrologic and water-quality effects of the potential outlet alternatives that were selected on the basis of the scenario analysis.

Given potential future lake levels and sulfate concentrations generated using either the scenario or stochastic approach and potential future ambient flows and sulfate concentrations for the Sheyenne River receiving waters, daily outlet discharges could be calculated for virtually any outlet alternative. For the scenario approach, future ambient flows and sulfate concentrations for the Sheyenne River were generated using the same sequence of years used for generating water-balance data for Devils Lake. For the stochastic approach, a procedure was developed for generating daily Sheyenne River flows and sulfate concentrations that were "in-phase" with the generated water-balance data for Devils Lake.

Simulation results for the scenario approach indicated that neither of the West Bay outlet alternatives provided effective flood-damage reduction without exceeding downstream water-quality constraints. However, both Pelican Lake outlet alternatives provided significant flood-damage reduction with only minor downstream water-quality changes. The most effective alternative for controlling rising lake levels was a Pelican Lake outlet with a 480-cubic-foot-per-second pump capacity and a 250-milligram-per-liter downstream sulfate constraint. However, this plan is costly because of the high pump capacity and the requirement of a control structure on Highway 19 to control the level of Pelican Lake. A less costly, though less effective for flood-damage reduction, plan is a Pelican Lake outlet with a 300-cubic-foot-per-second pump capacity and a 250-milligram-per-liter downstream sulfate constraint. The plan is less costly because the pump capacity is smaller and because the control structure on Highway 19 is not required. The less costly Pelican Lake alternative with a 450-milligram-per-liter downstream sulfate constraint rather than a 250-milligram-per-liter downstream sulfate constraint was identified by the U.S. Army Corps of Engineers as the preferred alternative for detailed design and engineering analysis.

Simulation results for the stochastic approach indicated that the geologic history of lake-level fluctuations of Devils Lake for the past 2,500 years was consistent with a climatic history that consisted of two climate states--a wet state, similar to conditions during 1980-99, and a normal state, similar to conditions during 1950-78. The transition times between the wet and normal climatic periods occurred randomly. The average duration of the wet climatic periods was 20 years, and the average duration of the normal climatic periods was 120 years.

The stochastic approach was used to generate 10,000 independent sequences of lake levels and sulfate concentrations for Devils Lake for water years 2001-50. Each trace began with the same starting conditions, and the duration of the current wet cycle was generated randomly for each trace. Each trace was generated for the baseline (natural) condition and for the Pelican Lake outlet with a 300-cubic-foot-per-second pump capacity and a 450-milligram-per-liter downstream sulfate constraint. The outlet significantly lowered the probabilities of future lake-level increases within the next 50 years and did not substantially increase the probabilities of reaching low lake levels or poor water-quality conditions during the same period.

INTRODUCTION

The Devils Lake Basin is a 3,810-square-mile subbasin of the Red River of the North (Red River) Basin (fig. 1). About 3,320 square miles of the total 3,810 square miles is tributary to Devils Lake and the remainder is tributary to Stump Lake. At a level of 1,446.5 feet above sea level, Devils Lake begins to spill into Stump Lake, and at a level of about 1,459 feet above sea level, the combined Devils Lake and Stump Lake system begins to spill from Stump Lake, through Tolna Coulee, to the Sheyenne River (fig. 2).

SEE FIGURE 1 ON NEXT PAGE.

Lake levels of Devils Lake were recorded sporadically from 1867 to 1890. In 1901, the U.S. Geological Survey (USGS) established a gaging station on Devils Lake. From 1867 through 2001, the lake level fluctuated between a minimum of 1,400.9 feet above sea level (nearly dry) in 1940 and a maximum of 1,448.0 feet above sea level in July 2001 (fig. 3). From 1993 to 2001, Devils Lake rose more than 25 feet. During that time, the surface area of the lake increased by about 140 square miles (from 68 to 205 square miles), and the volume increased by about 2 million acre-feet (from 0.6 to 2.5 million acre-feet). Because of the rising lake level, more than 50,000 acres of farmland and numerous roads and

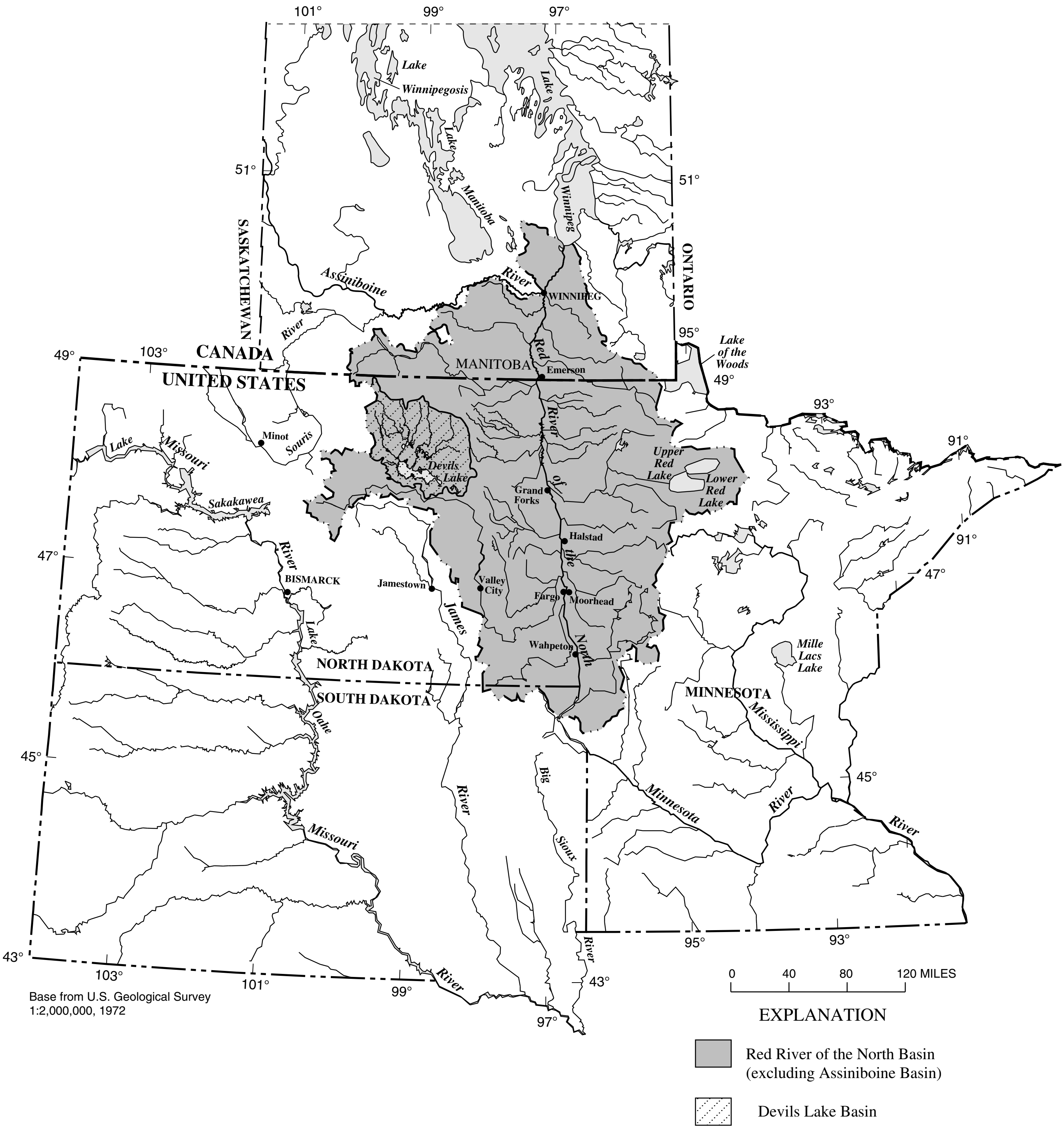

Figure 1. Locations of the Devils Lake Basin and the Red River of the North Basin.

SEE FIGURE 2 ON NEXT PAGE.

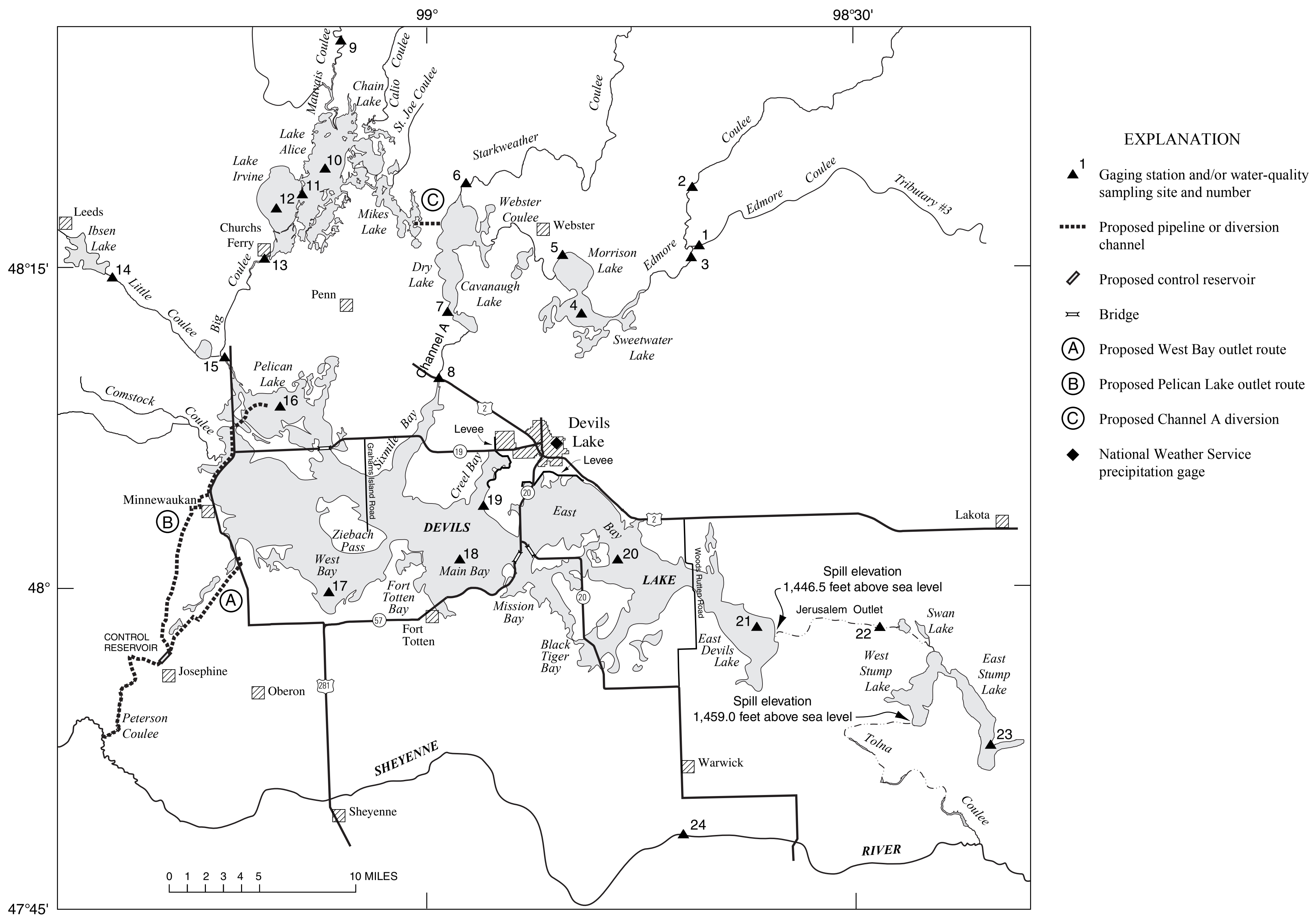

Figure 2. Locations of gaging stations and water-quality sampling sites in the Devils Lake Basin and proposed outlet routes for West Bay and Pelican Lake. (Level of Devils Lake is 1,445 feet above sea level.)

SEE FIGURE 3 ON NEXT PAGE.

highways around the lake have been flooded. Flood damages in the basin during 1993-99 exceeded $400 million (Bruce Engelhardt, North Dakota State Water Commission, oral commun., 2001).

Devils Lake could rise to levels much higher than 1,448.0 feet above sea level in future years, causing extensive additional flood damages in the basin and, in the event of an uncontrolled natural spill, downstream in the Red River Basin as well. According to Murphy and others (1997), Stump Lake (and, thus, Devils Lake) was above the natural spill elevation of Stump Lake (1,459.0 feet above sea level) at least twice in the past 4,000 years. Wiche and others (2000) used hydrological data and historical accounts of early explorers in the Devils Lake Basin to conclude the most recent spill from Devils Lake to Stump Lake before 2000 occurred sometime between 1820 and 1840. Therefore, the lake level (1,448.0 feet above sea level) in July 2001 was the highest lake level in more than 160 years.

Because of the potential for continued lake-level rises of Devils Lake, Congress directed the U.S. Army Corps of Engineers (Corps) to complete preconstruction engineering and design and an associated Environmental Impact Statement (EIS) for an emergency outlet from Devils Lake. The directive from Congress stipulates that, before construction of the emergency outlet can begin, the Corps must identify an outlet design that is technically sound and in compliance with the National Environmental Policy Act (NEPA) of 1969 and demonstrate the outlet is economically justified. Several outlet alternatives are being considered by the Corps (U.S. Army Corps of Engineers, 2002) to divert water from the west end of Devils Lake into the Sheyenne River upstream of Warwick (fig. 2). However, because the water in Devils Lake is more saline than ambient streamflow in the Sheyenne River, a potential outlet will affect water quality downstream of the outlet discharge location. Also, Devils Lake is an important fishery and recreational resource for the region and a potential outlet will affect the lake levels and water quality of the lake. Therefore, an outlet simulation model was needed to determine the potential effects of the various outlet alternatives on downstream water quality, downstream reservoir operation, and lake

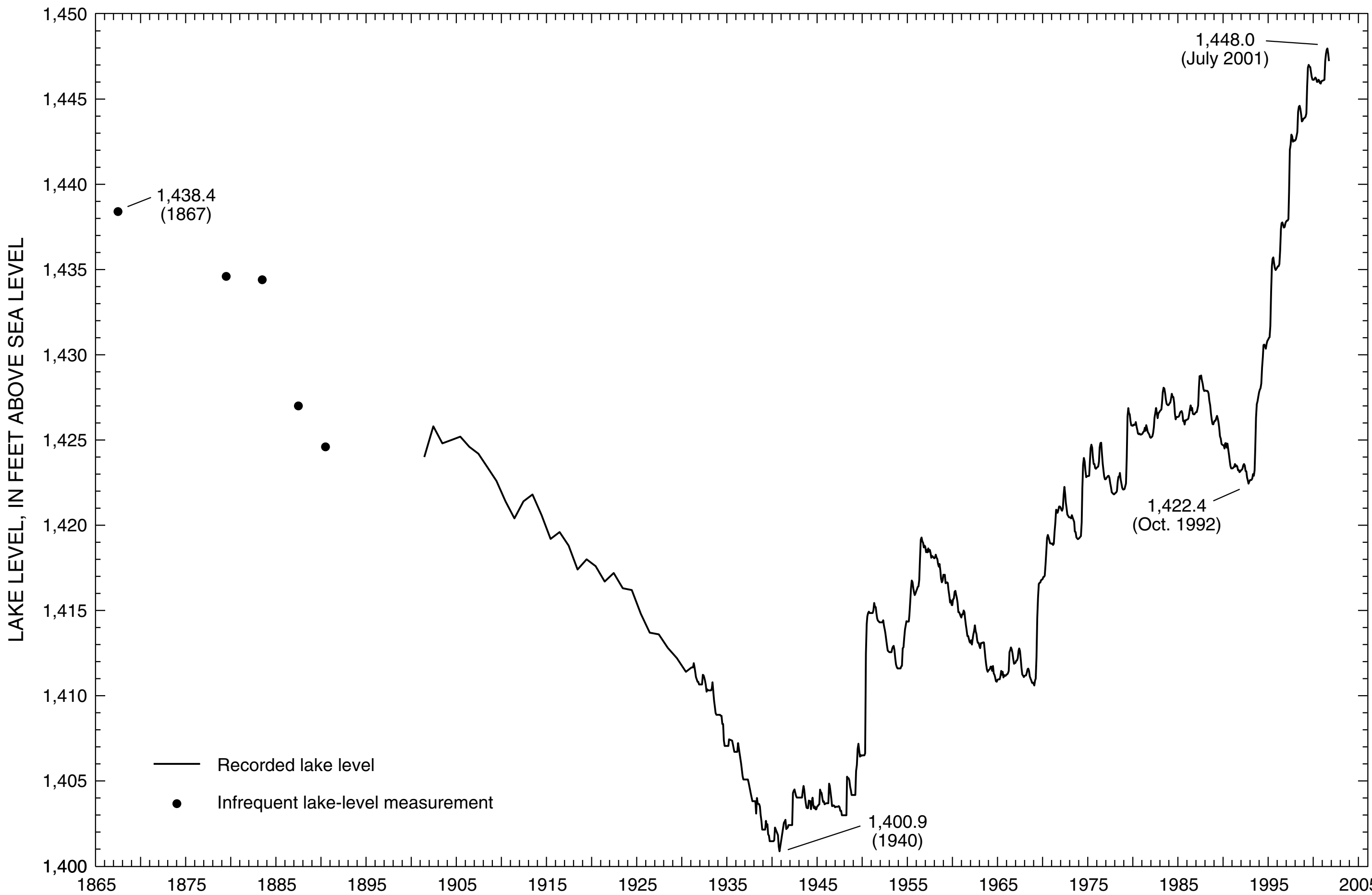

Figure 3. Recorded lake level for Devils Lake, 1867-2001.

levels and water quality of Devils Lake and to aid in the selection of a preferred alternative for detailed design and an environmental impact assessment.

A study was undertaken by the USGS, in cooperation with the Corps, to develop a model to simulate future operation of a proposed emergency outlet from Devils Lake to the Sheyenne River. This report describes the outlet simulation model, presents simulation results showing the potential effects of several proposed outlet alternatives on the lake levels and water quality of Devils Lake, and describes data from the simulation model that were used by the Corps to evaluate the economic viability and downstream effects of the proposed outlet.

Many individuals contributed to the successful completion of this study. James LaBaugh and Robert Lent of the USGS provided insight and guidance throughout the study and also served as colleague reviewers for the report. Daniel Reinartz of the Corps provided data and advice throughout the study and also ensured that the outlet simulation model met the needs of the Corps and its contractors. Patrick Foley, Dennis Holme, and James Sentz of the Corps provided technical insight throughout the modeling effort, and Joe Manous of the United States Military Academy at West Point provided data and expertise for developing the sulfate mass-balance model for Devils Lake. David Parkhurst and Jerad Bales of the USGS also provided expertise for developing the sulfate mass-balance model, and Bruce Engelhardt and James Landenberger of the North Dakota State Water Commission provided data and expertise for developing the water mass-balance model. Gregg Wiche, Wayne Berkas, and Robert Lundgren of the USGS provided advice and assistance throughout the study, and Cathy Martin of the USGS provided editorial assistance for the report.

METHODOLOGY USED TO DEVELOP OUTLET SIMULATION MODEL

The outlet simulation model was developed in several stages and each stage was verified before the next stage was started. In the first stage, recorded precipitation, evaporation, inflow, and lake-level data were used to develop a monthly water-balance model for the Devils Lake system. A regression model was used to obtain unbiased estimates of monthly precipitation, evaporation, and inflow for Devils Lake on the basis of the limited recorded data.

In the second stage, a detailed water mass-balance model was developed to compute the changes in volume for each of six major storage compartments--West Bay north of Highway 19, West Bay south of Highway 19, Main Bay, East Bay, East Devils Lake, and Stump Lake (fig. 2)--in response to monthly precipitation, evaporation, inflow, and outflow. The detailed water mass-balance model was constrained so the combined water balance for all six compartments coincided with the monthly water balance developed in the first stage for the Devils Lake system.

In the third stage, a detailed sulfate mass-balance model was developed to compute the changes in dissolved sulfate loads for each of the six major storage compartments on the basis of inflow, outflow, benthic flux of sulfate from bottom sediments, and wind- or buoyancy-induced mixing between compartments. Dissolved sulfate is considered to be the key water-quality constituent for evaluating the effects of the proposed outlet on downstream water quality. Coefficients that control the flux of sulfate from bottom sediments and the mixing between compartments were estimated using a nonlinear regression model to minimize the sum-of-squared errors between recorded and computed dissolved sulfate concentrations for each compartment.

In the fourth stage, the detailed water and sulfate mass-balance models were modified to include an outlet from Devils Lake to the Sheyenne River. Daily Sheyenne River streamflows and sulfate concentrations and monthly Devils Lake sulfate concentrations were used to compute daily outlet discharges for the outlet alternative being considered. The outlet discharges were computed to meet channel-capacity and water-quality constraints at the outlet insertion point. The effects of the various outlet alternatives on future lake levels and sulfate concentrations were evaluated for a hypothetical "wet scenario" in which Devils Lake would continue to rise to its natural spill elevation during the next 20 years. Simulation results for the wet scenario were used to evaluate outlet alternatives in terms of controlling rising lake levels and minimizing effects on downstream water quality.

In the final stage, a statistical time-series model was developed to stochastically generate monthly water-balance data for Devils Lake. The model, which was calibrated using recorded monthly water-balance data and verified using the geologic history of lake-level fluctuations of Devils Lake, was used to generate 10,000 independent sequences of monthly water-balance data for 2001-50. These sequences of data were, in turn, used to generate 10,000 future lake-level "traces" and sulfate concentrations for Devils Lake for a baseline (without-outlet) condition and for several outlet alternatives to allow the Corps to probabilistically evaluate the economic benefits and costs of an outlet and to determine the effects of the various alternatives on downstream water quality (U.S. Army Corps of Engineers, 2002).

MONTHLY WATER-BALANCE MODEL FOR DEVILS LAKE SYSTEM

Long-term fluctuations in lake levels (and volumes) of Devils Lake are controlled largely by precipitation on the lake surface, evaporation from the lake surface, and surface inflow (Wiche, 1986). Although some interaction may occur between Devils Lake and the underlying ground-water aquifer, past studies have indicated ground-water losses or gains are a small component of the overall water balance for the lake. Pusc (1993) indicated ground-water flow paths are predominately toward Devils Lake and a maximum of 5,000 acre-feet of annual ground-water inflow can be expected in any given year. By comparison, precipitation on the lake surface during 1997 was about 181,000 acre-feet, and inflow from Big Coulee and Channel A for 1997 was 489,000 acre-feet. For this study, a monthly water-balance model was developed to compute the changes in total volume of Devils Lake. A regression model was used to estimate monthly water-balance data on the basis of limited recorded data. The water-balance data estimated for this study confirm that ground-water interaction is a negligible component of the overall water balance.

Precipitation, Evaporation, and Inflow Data

For this study, actual precipitation on the lake surface was estimated using published precipitation data from the National Weather Service (NWS) precipitation gage at Devils Lake (fig. 2). Precipitation was assumed to be constant over the entire lake surface because too few data were available to determine the spatial distribution of the precipitation. The actual average daily precipitation on the lake surface might vary substantially from the published data, but for the monthly time step used for model development, the published data were sufficient to develop estimates of precipitation on the lake surface.

Evaporation from the lake surface was estimated using preliminary evaporation data developed by Wiche and Vecchia (1996). Wiche (1992) used detailed hydrometeorological data along with energy-budget methods to measure Devils Lake evaporation for 1986-88, but direct measurements of evaporation were unavailable for other years. For this study, methods described by Wiche and Vecchia (1996) were used to estimate monthly pan evaporation at Devils Lake on the basis of monthly pan-evaporation data from the U.S. Department of Agriculture Mandan and Dickinson Agricultural Experiment Stations (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1951-94). Although Mandan is about 140 miles southwest of Devils Lake and Dickinson is about 200 miles southwest of Devils Lake, intermittent pan-evaporation data for Devils Lake for 1951-71 were closely correlated with the Mandan and Dickinson data. The estimated pan evaporation for Devils Lake was converted to estimated evaporation from the lake surface using established methods (Winter, 1981).

Surface inflow was estimated using lake-level records or daily mean discharge data from USGS gaging stations in the Devils Lake Basin. Before 1979, surface runoff from the northeast part of the Devils Lake Basin flowed through an interconnected chain of lakes (Sweetwater, Morrison, and Dry Lakes; fig. 2) and then through the natural outlet from Dry Lake into another interconnected chain of lakes (Mikes Lake, Chain Lake, Lake Alice, and Lake Irvine; fig. 2). Thus, all streamflow from the chain of lakes north of Devils Lake flowed downstream through Big Coulee into Devils Lake. In 1979, the Ramsey County and Cavalier County Water Management Boards constructed Channel A, which connects Dry Lake to Sixmile Bay on Devils Lake (fig. 2), and a levee was constructed across the natural outlet of Dry Lake. Thus, since 1979, streamflow from Sweetwater, Morrison, and Dry Lakes has discharged through Channel A into Devils Lake; and the remaining runoff has discharged along the natural watercourse through Big Coulee into Devils Lake. Lake-level records for Sweetwater, Morrison, and Dry Lakes and daily mean discharge data for upstream tributaries to those lakes were used to estimate inflow from Channel A for October 1979 to September 1983. Daily mean discharge data from gaging station 05056410 (Channel A near Penn, N. Dak.; site 8, fig. 2) were used for October 1983 to September 1999, when the gaging station was discontinued because of backwater from Devils Lake.

Inflow from Big Coulee (fig. 2) for 1950-97 was obtained from gaging station 05056400 (Big Coulee near Churchs Ferry, N. Dak.; site 15, fig. 2). Because the gaging station was moved upstream in March 1998 because of backwater from

Devils Lake, inflow from Big Coulee for March 1998 to September 1999 was estimated by adding data from gaging stations 05056270 (Big Coulee below Churchs Ferry, N. Dak.; site 13, fig. 2) and 05056340 (Little Coulee near Leeds, N. Dak.; site 14, fig. 2). Gaging station 05056270 was discontinued after September 1999. Additional inflows were added to the model for 1999 to account for increased storage in the upstream lakes during that year. Devils Lake rose to a peak elevation of 1,447.1 feet above sea level during 1999 and when the level of Devils Lake exceeds 1,445.0 feet above sea level, the water balance for Devils Lake includes Lakes Alice and Irvine (fig. 2).

For this report, estimated Devils Lake precipitation refers to precipitation at the NWS gage at Devils Lake, and estimated Devils Lake evaporation refers to evaporation from the lake surface as estimated according to methods described by Wiche and Vecchia (1996). Inflow from Big Coulee refers to all surface inflow into Devils Lake from sources upstream of the original gaging station (05056400) near Churchs Ferry, gaged inflow to Devils Lake refers to total inflow from Big Coulee and Channel A, and ungaged inflow to Devils Lake refers to all inflow from overland flow or from small tributaries that drain areas adjacent to Devils Lake.

Potential Nonstationarity of Precipitation, Evaporation, and Inflow

An important assumption for the Devils Lake outlet simulation model is that the climatic variables (precipitation and evaporation) are stationary; that is, recent climatic conditions are representative of future climatic conditions. To determine the validity of this assumption, estimated annual and quarterly precipitation and evaporation totals for 1950-99 were obtained from estimated Devils Lake precipitation and evaporation data. The estimated annual and quarterly precipitation totals indicate a higher frequency of wet years in the last half of the record than in the first half (fig. 4). Of the 10 highest annual totals, 9 occurred during 1975-99. Considering the quarterly totals, the tendency for wetter conditions during 1975-99 was particularly evident in the summer and fall quarters; 8 of the 10 highest summer totals and all of the 10 highest fall totals occurred during the last half of the record.

The estimated annual and quarterly precipitation totals also indicate a lower frequency of dry years in the last half of the record than in the first half (fig. 4). Of the 10 lowest annual totals, only 3 occurred during 1975-99. However, considering the quarterly totals, the tendency for fewer dry years during 1975-99 occurred only in the spring and summer quarters. In the winter quarter, the number of dry years was evenly divided between the first and last halves of the record, and in the fall quarter, more dry years occurred during 1975-99. Thus, conditions during the fall quarter were more variable during 1975-99 than during 1950-74 as indicated by the higher frequency of both wet and dry years during 1975-99.

The estimated annual and quarterly evaporation totals indicate a higher frequency of low-evaporation years in the last half of the record than in the first half (fig. 5). Of the 10 lowest annual totals, 6 occurred during 1975-99. Considering the quarterly totals, 6 of the 10 lowest spring, summer, and fall totals occurred during the last half of the record. These results are consistent with those that indicate wetter conditions during 1975-99 for the summer and fall quarters because a higher frequency of cloudy, wet days during the summer and fall generally reduces evaporation.

The estimated annual and quarterly evaporation totals also indicate a higher frequency of high-evaporation years in the last half of the record than in the first half (fig. 5). Of the 10 highest annual totals, 6 occurred during 1975-99. Considering the quarterly totals, 8 of the 10 highest spring totals, 7 of the 10 highest winter and fall totals, and 6 of the 10 highest summer totals occurred during the last half of the record. Thus, evaporation was more variable during 1975-99 than during 1950-74. For the fall quarter, these results are consistent with those that indicate precipitation was more variable during 1975-99 than during 1950-74, but for the spring and summer quarters, the results are not consistent. During those quarters, the tendency for high evaporation was not accompanied by a tendency for low precipitation, possibly because climatic conditions during the spring and summer were both wetter and warmer during 1975-99 than during 1950-74.

Statistical hypothesis tests used to determine if a significant increase in precipitation occurred between the first and last halves of the record indicated the apparent increase in precipitation was significant (table 1). For all three tests, the null hypothesis was that the probability distribution of precipitation was the same for both time periods. The alternative hypothesis for the Wilcoxon rank-sum test was that the median of the precipitation distribution was higher for 1975-99 than for 1950-74, and the alternative hypothesis for the t-test was that the mean of the precipitation distribution was higher for 1975-99 (Helsel and Hirsch, 1992). The alternative hypothesis for the hypergeometric test was that a higher frequency

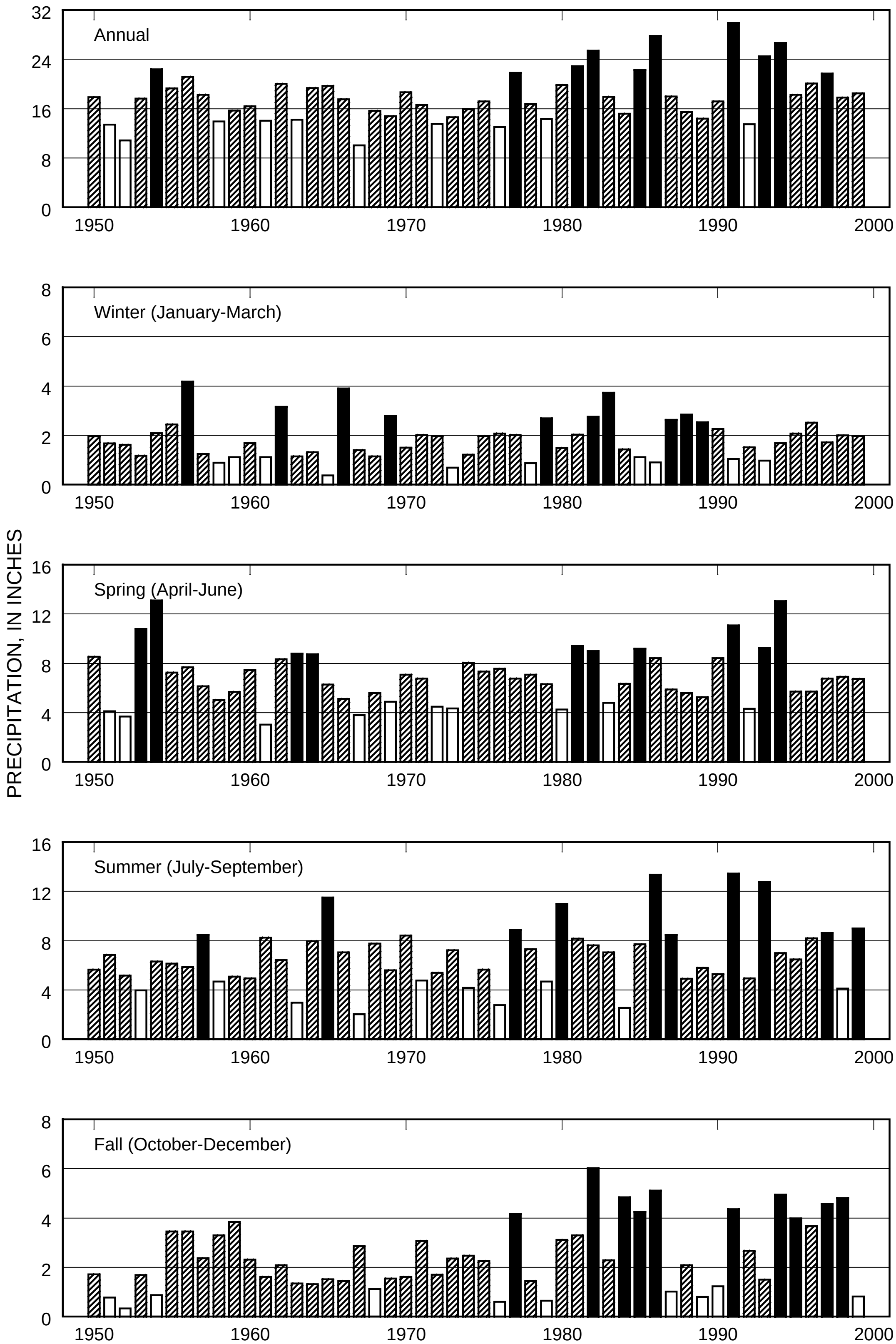

Figure 4. Estimated annual and quarterly precipitation totals for Devils Lake for 1950-99. (Darkest bars indicate 10 highest values, and lightest bars indicate 10 lowest values.)

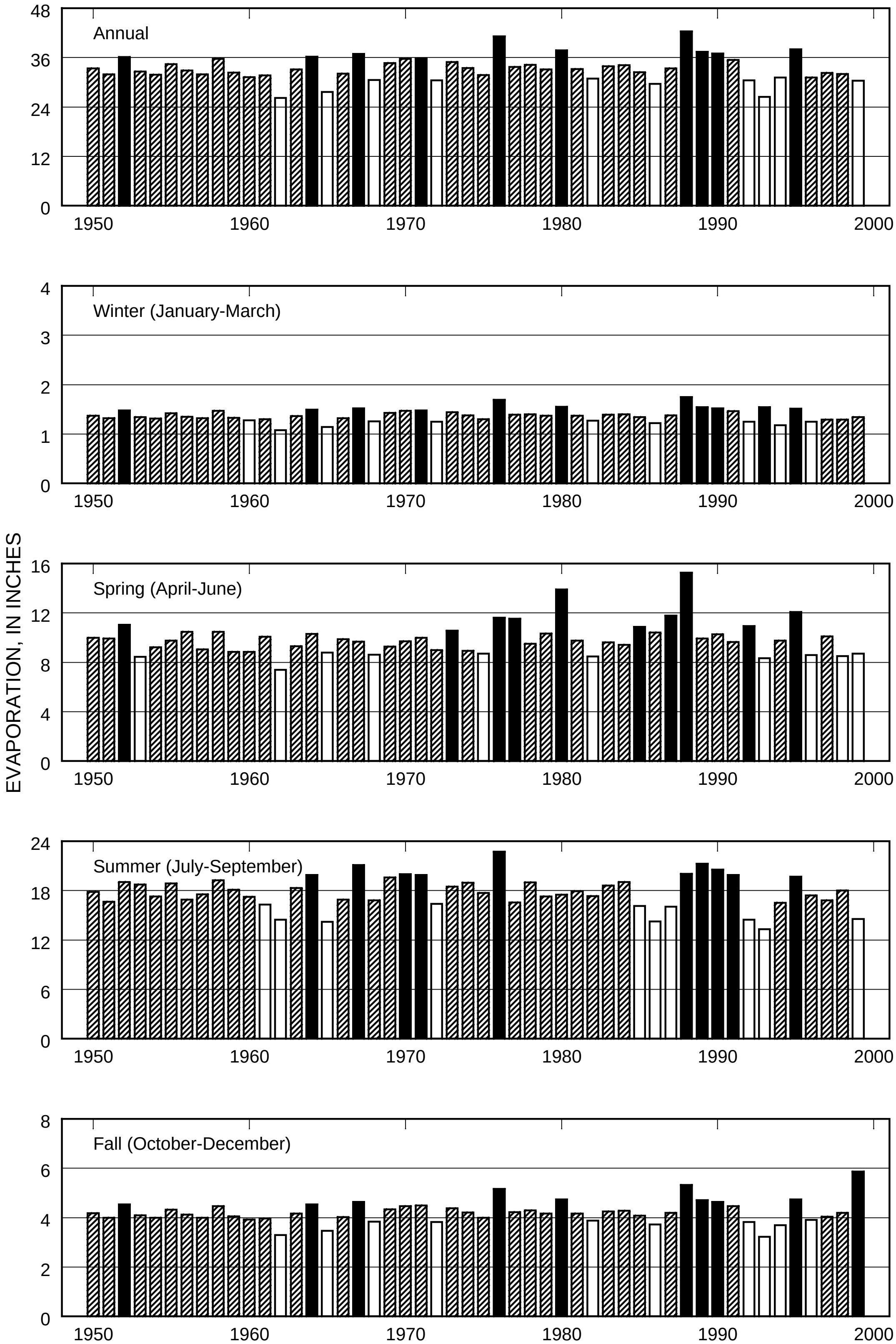

Figure 5. Estimated annual and quarterly evaporation totals for Devils Lake for 1950-99. (Darkest bars indicate 10 highest values, and lightest bars indicate 10 lowest values.)

Table 1. Results of statistical hypothesis tests to determine if Devils Lake precipitation was higher during 1975-99 than during 1950-74

[<, less than]

	p-value[1]		
	Wilcoxon rank-sum test	**t-test**	**Hypergeometric test**
Winter	0.086	0.198	0.363
Spring	.124	.153	.360
Summer	[2].048	[2].035	[2].037
Fall	[2].035	[3].007	[3]<.001
Annual	[2].011	[3].003	[3].005

[1]The p-value is the probability that the test statistic could have exceeded the recorded value by chance under the null hypothesis that the probability distribution of precipitation was the same for both time periods.

[2]Significant increase detected for 1975-99 (p-value less than 0.05).

[3]Highly significant increase detected for 1975-99 (p-value less than 0.01).

of wet years occurred during 1975-99. The hypergeometric test was based on the observation that, under the null hypothesis, the number of the 10 highest precipitation amounts that occurred during the second half of the record had a hypergeometric distribution with an expected value of 5 and a variance of 2.04 (Devore, 1987). For all three tests, precipitation totals were assumed to be independent from year to year.

The small p-values for all three tests (table 1) confirmed the significance of the increase in annual precipitation during 1975-99. For example, for the hypergeometric test, the chance was only 0.005, or 1 in 200, under the null hypothesis that at least 9 of the 10 highest annual totals would occur during 1975-99. Considering the quarterly precipitation totals, all three tests indicated moderately significant increases (p-values less than 0.05) for the summer, and two tests indicated highly significant increases (p-values less than 0.01) for the fall. None of the tests indicated significant increases for the winter or spring. Results from the hypergeometric test were particularly noteworthy for the fall quarter. The chance was less than 0.001, or 1 in 1,000, under the null hypothesis that all 10 of the highest fall totals would occur during the last half of the record.

Although the statistical tests indicated a significant increase in precipitation occurred in the Devils Lake Basin sometime during the mid- to late 1970’s, a definitive cause for the increase is not known. Evidence indicates precipitation patterns in the basin are related to an increased frequency of sea-surface temperature anomalies in the equatorial Pacific, and according to Montroy (1997), the activity of these temperature anomalies, known as El Nino and La Nina, has been higher since 1977 than at any other time during the 20th century. The temperature anomalies, along with atmospheric pressure anomalies in the northern Atlantic and Pacific Oceans, affect the position of the jet stream across the United States and Canada from season to season and from year to year; and the position of the jet stream, in turn, affects precipitation and temperature patterns across the Devils Lake Basin. The most noticeable effect on the Devils Lake Basin has been an increased frequency of storms bearing Gulf of Mexico moisture across the basin, particularly during the summer and fall (Osborne, 2000).

Baldwin and Lall (2000) related the recent climatic conditions in the Devils Lake Basin to interannual and interdecadal atmospheric circulation patterns and concluded that climatic conditions in the Devils Lake Basin (and elsewhere in the upper Midwest) are subject to long-term fluctuations in the circulation patterns. However, the fluctuations may be caused by natural long-term climatic variability rather than by other factors such as global warming. Baldwin and Lall (2000) also concluded that, although the link between global atmospheric circulation patterns and Devils Lake climatic variability is strong, predicting future climatic conditions in the Devils Lake Basin is beyond the current state of the art.

As indicated in the previous discussion, precipitation and evaporation in the Devils Lake Basin during the past 50 years cannot be assumed to be stationary and independent from year to year. Rather, an abrupt change that coincided with an increased frequency of sea-surface temperature anomalies occurred in about 1977. Whether the change was a result of natural climatic variability or of climate change is not known, but evidence indicates climatic conditions in the Devils Lake Basin during the early 1800's were at least as wet as conditions that exist today, and conditions were much wetter than current conditions several times during the past 5,000 years (Murphy and others, 1997; Wiche and others, 2000). The effect of climate nonstationarity on estimated probabilities of future lake levels will be evaluated in a later section of this report.

Although precipitation and evaporation during 1975-99 appear to be relatively homogeneous and no obvious differences exist between1993-99 (the period of rapid rises in the level of Devils Lake) and 1975-92, gaged inflow to Devils Lake (fig. 6) during 1993-99 was substantially higher than before 1993 for all four quarters. The wetter conditions beginning in about 1977 do not appear to increase the frequency of high inflows for more than a decade. However, except for 1990 and 1991, all of the low-inflow years occurred during the first half of the record. This indicates the change to wetter conditions in about 1977 probably resulted in an immediate decrease in the frequency of low inflows.

To understand why the high inflows did not occur until 1993-99 requires an understanding of the hydrology of the Devils Lake Basin. The basin is typical of the "prairie-pothole region" of the north-central United States and south-central Canada and has a flat topography with many small lakes and wetlands. During the 1960's and early 1970's, which generally was a period of low precipitation and high evaporation (figs. 4 and 5), the water levels in the lakes and wetlands were low, and much of the upper Devils Lake Basin did not contribute flow to Devils Lake. With the onset of wet conditions in the late 1970's, the water levels began to rise, and soil moisture began to be replenished. A drought during 1987-92 reversed the trend, and the water levels began to decline. Wet conditions returned in the summer of 1993 and produced the highest summer and fall inflows on record (fig. 6). These wet conditions saturated much of the upper Devils Lake Basin, and as wet conditions continued in subsequent years, the small lakes and wetlands began to fill and the number of small subbasins that comprise the contributing drainage area of Devils Lake began to increase. The greater contributing drainage area, in turn, resulted in higher inflows during 1993-99.

Estimation of Monthly Water-Balance Data for 1980-99

Monthly water-balance data for 1980-99 were estimated on the basis of limited recorded data. A monthly water-balance equation was developed to compute the changes in total volume of Devils Lake in response to precipitation, evaporation, and inflow. However, because exact values were unavailable for monthly precipitation, evaporation, and inflow and for monthly changes in volume, a multiple-regression model was used to reduce bias and remove noise from the water-balance equation. A monthly time step was used because noise in lake-volume determinations, precipitation, evaporation, and inflow makes it difficult to determine an accurate water balance on a daily time step. The multiple-regression model was developed using monthly changes in volume for 1980-99. That period was used to avoid complications related to rerouting of flow with the construction of Channel A in 1979.

Monthly volumes of Devils Lake were estimated using lake-level data from gaging station 05056500 (Devils Lake near Devils Lake, N. Dak.; site 19, fig. 2). The elevation-volume equations used are described in detail in appendix A. Although the lake-level data contain negligible bias and are highly accurate (+/-0.01 foot), lake levels across Devils Lake can vary from those at the gaging station because of significant wind- and inflow-induced hydraulic gradients from west to east across the lake. Therefore, to obtain an estimated lake level under calm conditions for the end of each month, the lake-level records for near the end of each month were examined manually and the effects of the wind-induced lake-level fluctuations were estimated and removed from the lake-level data. According to Manous (2000), the wind-induced head differences at the Highway 20 and Highway 57 bridge openings (fig. 2) during the summer of 1998 when the level of Devils Lake was about 1,444 feet above sea level generally was less than 1 inch (in absolute value) and the maximum was about 1.4 inches. Although those locations differ from the gaging-station location, daily lake-level records and meteorological conditions at Devils Lake indicated that a range of plus or minus 1.5 inches was a good estimate of potential wind-induced noise in recorded lake levels at the gaging station. Therefore, if significant wind effects existed, the recorded lake levels were adjusted within a range of plus or minus 1.5 inches (0.125 foot). The resulting monthly lake levels represented "wind-adjusted" lake levels at the gaging station within an accuracy of about 0.05 foot and were used to develop the water-balance equation.

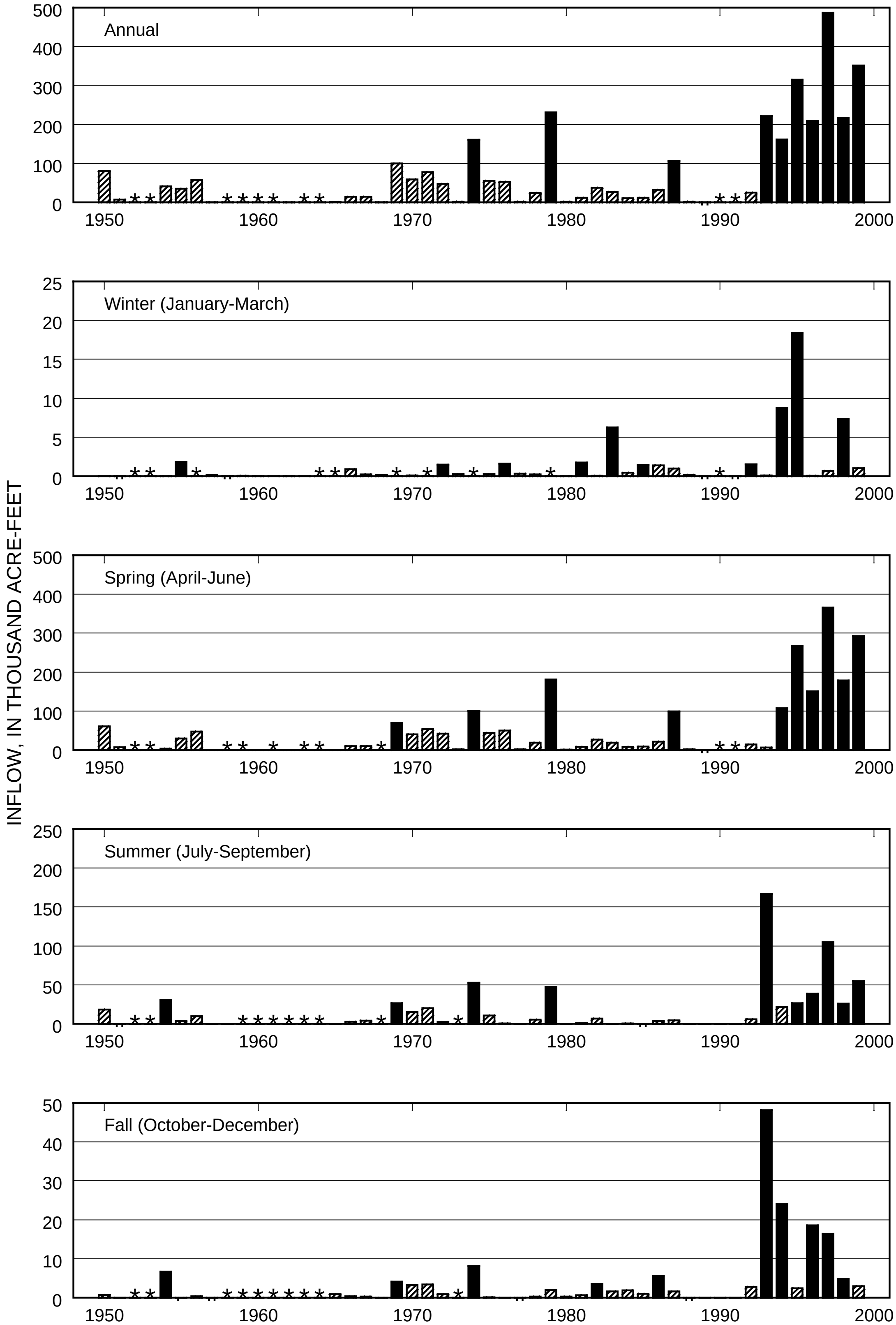

Figure 6. Gaged inflow to Devils Lake (inflow from Big Coulee and Channel A) for 1950-99. (Darkest bars indicate 10 highest values, and asterisks indicate 10 lowest values.)

The effects of spatially varying lake levels on the total volume of Devils Lake were more difficult to assess than the effects of wind because gaging station 05056500 is the only lake gage on Devils Lake. The North Dakota State Water Commission used a global positioning system to conduct a detailed survey of lake levels on May 15, 2001 (a period of high surface inflow to the lake), and showed that the lake level at the east end of East Devils Lake on that day was 1,447.5 feet above sea level. On that same day, the level at the lake gage was 1,447.7 feet above sea level, and the level at gaging station 05056255 (Lake Alice-Irvine Channel near Churchs Ferry, N. Dak.; site 11, fig. 2) was 1,447.9 feet above sea level (Lakes Alice and Irvine were part of Devils Lake at that time). The lake levels at the east end of East Devils Lake and at gaging station 05056255 indicate a difference of 0.4 foot from west to east is entirely possible, and even higher differences can occur during periods of higher inflow. However, the level at the lake gage, which is centrally located along the flow gradient, should be a reasonable estimate of the average lake level for the entire lake. Therefore, to compute the total volume of Devils Lake, the level at the lake gage was used for the lake level of the entire lake at the end of each month. Because East Devils Lake was separated from the rest of Devils Lake during 1988-92, the total volume of Devils Lake for that period was adjusted to account for differences in the estimated lake levels of Devils Lake and East Devils Lake (Wiche and Vecchia, 1996).

The previous discussion indicates errors in estimated monthly lake volumes may exist, but the errors should not cause significant bias in the water balance. However, bias may be caused by errors in precipitation, evaporation, and inflow values. Therefore, the following regression model was used as a first approximation to smooth the errors and remove the bias:

$$V(t) - V(t-1) = a\frac{P'(t)}{12}A(t-1) - b\frac{E'(t)}{12}A(t-1) + (1+c)G(t) + e(t) \tag{1}$$

where

$V(t)$ is the estimated volume of Devils Lake at the end of month t, in acre-feet;

$P'(t)$ is estimated Devils Lake precipitation in month t, in inches;

$A(t)$ is the estimated area of Devils Lake at the end of month t, in acres;

$E'(t)$ is estimated Devils Lake evaporation in month t, in inches;

$G(t)$ is gaged inflow (total inflow from Big Coulee and Channel A) in month t, in acre-feet;

$e(t)$ is the error for month t; and

a, b, and c are regression coefficients.

For this report, equation 1 will be referred to as the regression model with constant coefficients to distinguish it from the subsequent model in which the coefficients were allowed to vary from month to month. The volume difference on the left-hand side of the equation will be referred to as the estimated change in volume for the given month. The assumption was made that the estimated change in volume is an unbiased estimate of the exact change in volume.

The estimated and fitted monthly changes in volume from the regression model with constant coefficients are shown in figure 7. The coefficients were estimated using ordinary least-squares regression, and the estimated values were a = 0.97, b = 0.99, and c = 0.17. These values indicate that the best (that is, minimum mean-squared error) estimator of monthly changes in volume is obtained by assuming precipitation on the lake surface was 3 percent less than estimated Devils Lake precipitation, evaporation on the lake surface was 1 percent less than estimated Devils Lake evaporation, and ungaged inflow to Devils Lake was 17 percent of gaged inflow. These values are reasonable, but the model residuals (fig. 8) indicate the estimated annual change in volume (the sum of the estimated monthly changes in volume) is 20,000 acre-feet per year higher, on average, than the fitted annual change in volume. The mean of the residuals is 1,660 acre-feet, which is a bias of about 20,000 (1,660 x 12) acre-feet per year. Although Devils Lake may receive a small amount of ground-water inflow, the bias in the residuals probably was not caused by ground-water inflow for two reasons. First, the bias is much too large to be attributed totally to ground water; and second, the bias is highly seasonal in nature

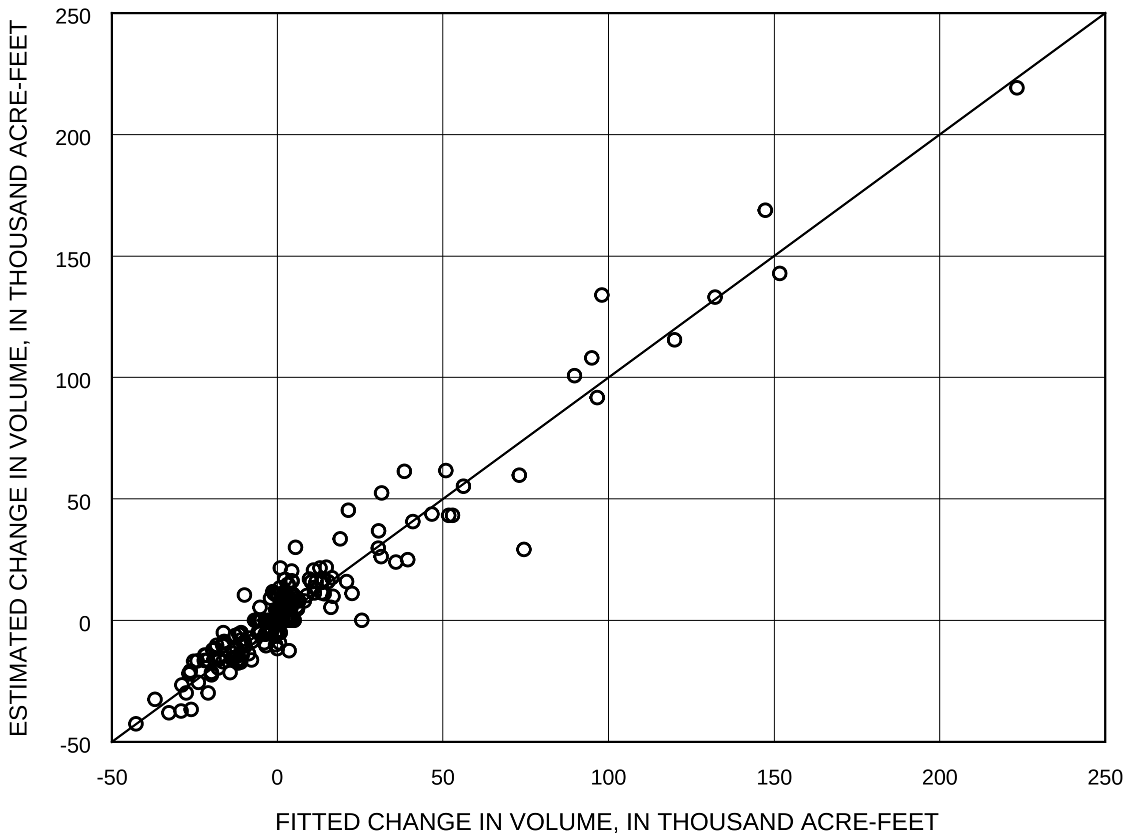

Figure 7. Estimated and fitted monthly changes in volume for Devils Lake for 1980-99 from regression model with constant coefficients. (Points indicate estimated changes, and line indicates fitted changes.)

(fig. 8). Although the model residuals indicate bias from February through July, no discernible bias is shown for August through January. A bias from ground-water inflow would be evident throughout the entire year and should be clear from late summer through the winter, when lake levels are most stable.

The bias in the residuals probably was caused largely by bias from the precipitation and evaporation values used in the model. Bias from the precipitation values could be from either (or both) of two sources--bias in measured precipitation at the Devils Lake gage or bias between actual precipitation at the Devils Lake gage and actual average precipitation on the lake surface. The first source of bias probably is significant. According to Yang and others (1998), significant undercatch of precipitation may occur when using precipitation gages such as those used at the city of Devils Lake. The undercatch increases as windspeed increases and is most evident during snowy conditions. For example, daily catch ratios (measured precipitation divided by actual precipitation) for snow commonly were less than 60 percent for windspeeds in excess of 14.4 miles per hour. Thus, measured precipitation at the Devils Lake gage probably was less than actual precipitation at the gage, especially during the winter and early spring. The second source of bias is difficult to evaluate because only one long-term NWS precipitation gage is located near the lake (fig. 2). Although differences in mean monthly precipitation on the surface of Devils Lake probably do exist, too few data are available to estimate the spatial distribution of the precipitation.

Bias from the evaporation values could be from several sources. For example, the methods described by Wiche and Vecchia (1996) to estimate monthly evaporation from the lake surface use a relation between class A pan-evaporation data for Devils Lake and class A pan-evaporation data for the Mandan and Dickinson Agricultural Experiment Stations. The relation was developed using data for 1951-71 and may differ from the current relation. In addition, the ratio between class A pan evaporation and lake-surface evaporation was estimated using established methods (Farnsworth and Thompson, 1982) and may not equal the actual ratio. The relation between pan evaporation and lake-surface evaporation during October through April is particularly difficult to assess.

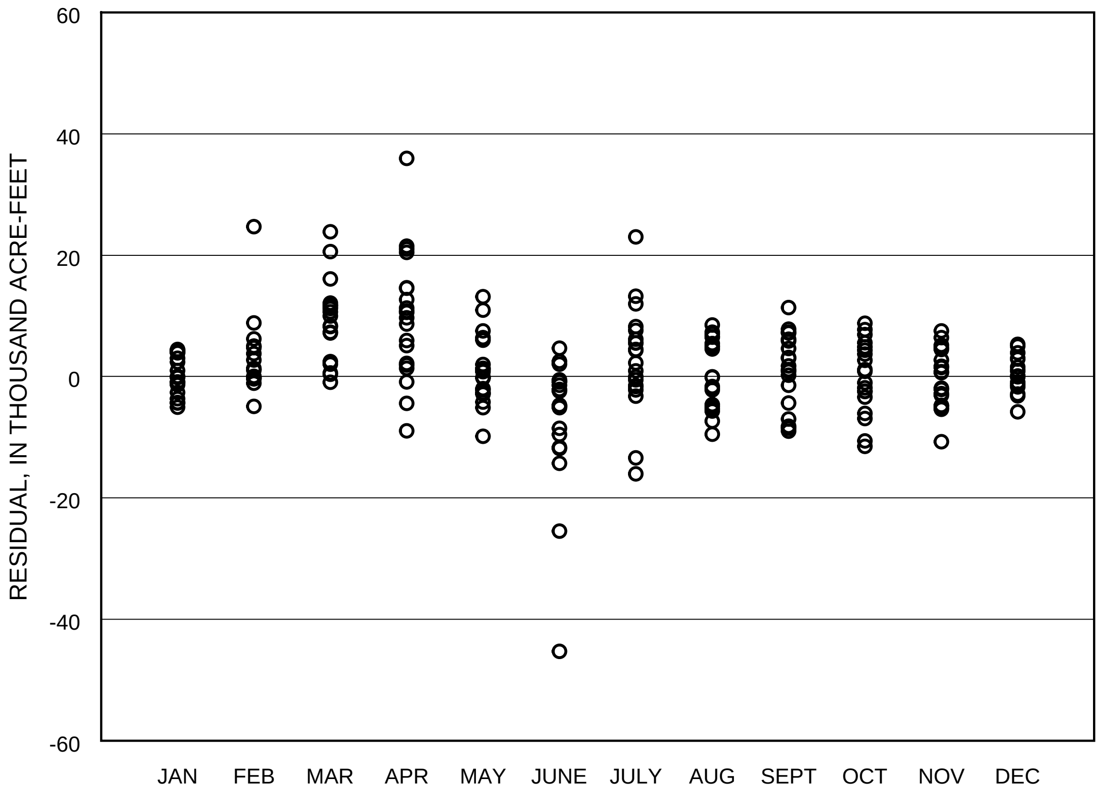

Figure 8. Residuals of estimated monthly changes in volume for Devils Lake for 1980-99 from regression model with constant coefficients.

The previous discussion indicates bias in precipitation and evaporation values for Devils Lake is likely to be seasonal in nature. Therefore, the regression model with constant coefficients (eq. 1) was modified in the following form:

$$V(t) - V(t-1) = a(m)\frac{P'(t)}{12}A(t-1) - b(m)\frac{E'(t)}{12}A(t-1) + [1 + c(m)]G(t) + e(t) \qquad (2)$$

where

$a(m)$, $b(m)$, and $c(m)$ are regression coefficients that depend on the month.

Although negligible bias occurs in the gaged inflow values, the coefficient that relates ungaged inflow $[c(m)G(t)]$ to gaged inflow was allowed to depend on the month because the relation between gaged inflow and ungaged inflow was not expected to be the same throughout the year.

In the regression model with monthly coefficients (eq. 2), separate coefficients were allowed for each month. The coefficients were estimated using ordinary least-squares regression, but several did not make sense physically. For example, $b(m)$ was negative during December-March, and $c(m)$ was slightly negative during several months. Therefore, $b(m)$ was set equal to zero during December-March when evaporation already tends to be quite low, and $c(m)$ was held constant for all months except March, April, and May because the estimates were significantly greater than zero during March-May but not significantly different from zero for the other months. The model then was refitted using ordinary least-squares regression. The estimated coefficients are given in table 2.

The estimated coefficients for precipitation were all greater than one, indicating fitted precipitation on the lake surface was greater than measured precipitation at the Devils Lake gage. The large coefficients for January through April probably were a result of more snow falling on the lake than measured at the city of Devils Lake. The coefficients also were high for August through October but were close to 1 for the remaining months. The estimated coefficients for evaporation were all

Table 2. Estimated coefficients for regression model used to compute monthly changes in volume for Devils Lake for 1980-99

Month	Coefficients for		
	Precipitation $[a(m)]$	Evaporation $[b(m)]$	Ungaged inflow $[c(m)]$
January	1.172	0	0.017
February	1.322	0	.017
March	1.346	0	.934
April	1.222	.901	.117
May	1.062	.840	.187
June	1.000	1.034	.017
July	1.070	.825	.017
August	1.174	.882	.017
September	1.191	.824	.017
October	1.103	.972	.017
November	1.010	.936	.017
December	1.029	0	.017

less than 1 except in June. Thus, fitted evaporation from the lake surface in most months was less than estimated Devils Lake evaporation. The small coefficients for July and September indicate that fitted evaporation from the lake surface was about 83 percent of estimated evaporation during those months. Fitted evaporation in June was about 3 percent greater than estimated evaporation. The estimated coefficients for ungaged inflow indicate that fitted ungaged inflow to Devils Lake was highest in March and was about 93 percent of gaged inflow to Devils Lake during that month. This value was reasonable considering runoff from ungaged sources near the lake probably reaches the lake sooner than gaged inflow during spring melt. Ungaged inflow in April and May was about 12 and 19 percent, respectively, of gaged inflow, and ungaged inflow during the remaining months was about 2 percent of gaged inflow. Although the estimated coefficient of 0.017 for the remaining months was not statistically different from zero (on the basis of a t-test with a significance level of 5 percent), a small amount of ungaged inflow was expected in those months, and the coefficient was kept in the model.

The estimated and fitted monthly changes in volume from the regression model with monthly coefficients are shown in figure 9. The detailed model did a much better job of fitting monthly changes in volume for Devils Lake than the regression model with constant coefficients (fig. 7). The model residuals (fig. 10) indicate no significant bias and generally are less than 10,000 acre-feet in absolute value. Given that the surface area of Devils Lake ranged from about 50,000 acres to 130,000 acres during 1980-99, a residual of 10,000 acre-feet easily could be attributed to errors in estimated lake levels. For example, an error of -0.05 foot in the lake level at the end of one month and +0.05 foot at the end of the next month would translate into an error of 10,000 acre-feet in the computed change in volume for a surface area of 100,000 acres. The mean of the residuals for all months is -151 acre-feet. Because this value is small and no physical basis exists for a negative intercept, no intercept was included in the model.

The time series of residuals, which was examined for any systematic variation with time, indicated the residuals were more variable during 1995-99 than during 1980-94 (fig. 11). The variation probably resulted from the larger surface area during 1995-99 producing more noise in volume calculations. The residuals are well scattered above and below zero during most of the record but in 1993 appear to be biased high, probably because of unusually high ungaged inflow during the summer flood of that year.

The water-balance equation developed for this study was used to develop a sophisticated model for Devils Lake that simulates both water quantity and water quality on a monthly time step. A consistent underestimation of precipitation and overestimation of inflow in the model would cause large errors in the chemical mass balance for Devils Lake, and an

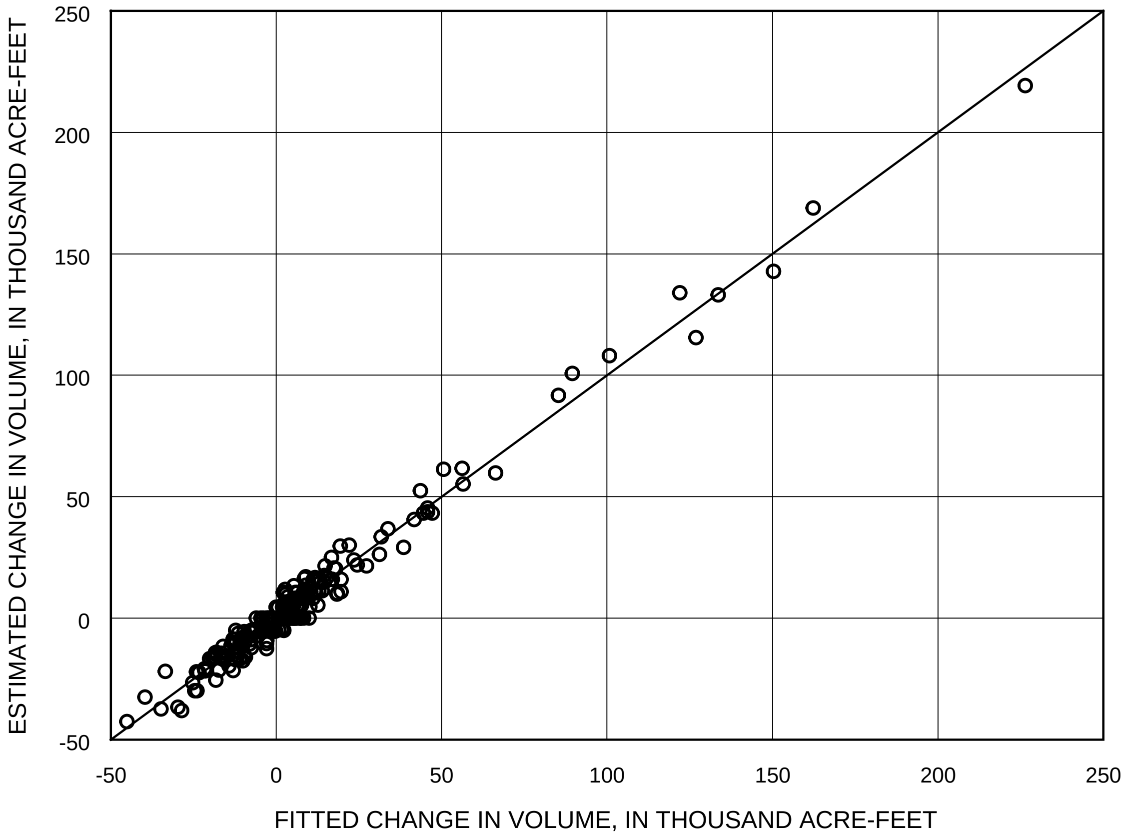

Figure 9. Estimated and fitted monthly changes in volume for Devils Lake for 1980-99 from regression model with monthly coefficients. (Points indicate estimated changes, and line indicates fitted changes.)

underestimation of changes in volume in some months and an overestimation in others would cause errors in the timing of changes in lake levels and errors in water quality within the year. Because these errors would, in turn, cause errors in the potential outlet discharges from Devils Lake to the Sheyenne River, the water-balance data used in model development needed to be as accurate as possible. Because of these considerations, the regression model with monthly coefficients (eq. 2) was used to compute adjusted monthly precipitation, evaporation, and inflow values for Devils Lake. The adjusted values, which were used in model development, were defined as the fitted values obtained from equation 2:

$$P(t) = a(m)P'(t), E(t) = b(m)E'(t), \text{ and } Q(t) = [1 + c(m)]G(t) \tag{3}$$

where

$P(t)$ is fitted precipitation on the lake surface in month t, in inches;

$E(t)$ is fitted evaporation from the lake surface in month t, in inches; and

$Q(t)$ is fitted total (gaged and ungaged) inflow in month t, in acre-feet.

The values for $a(m)$, $b(m)$, and $c(m)$ are given in table 2. The fitted values (P, E, and Q) for 1980-99 are given in appendix B and shown in figure 12 and will, henceforth, be referred to as the monthly water-balance data for Devils Lake. P, E, and Q will, henceforth, be referred to as monthly Devils Lake precipitation, evaporation, and total inflow with the understanding that they are estimates of the actual (unknown) values.

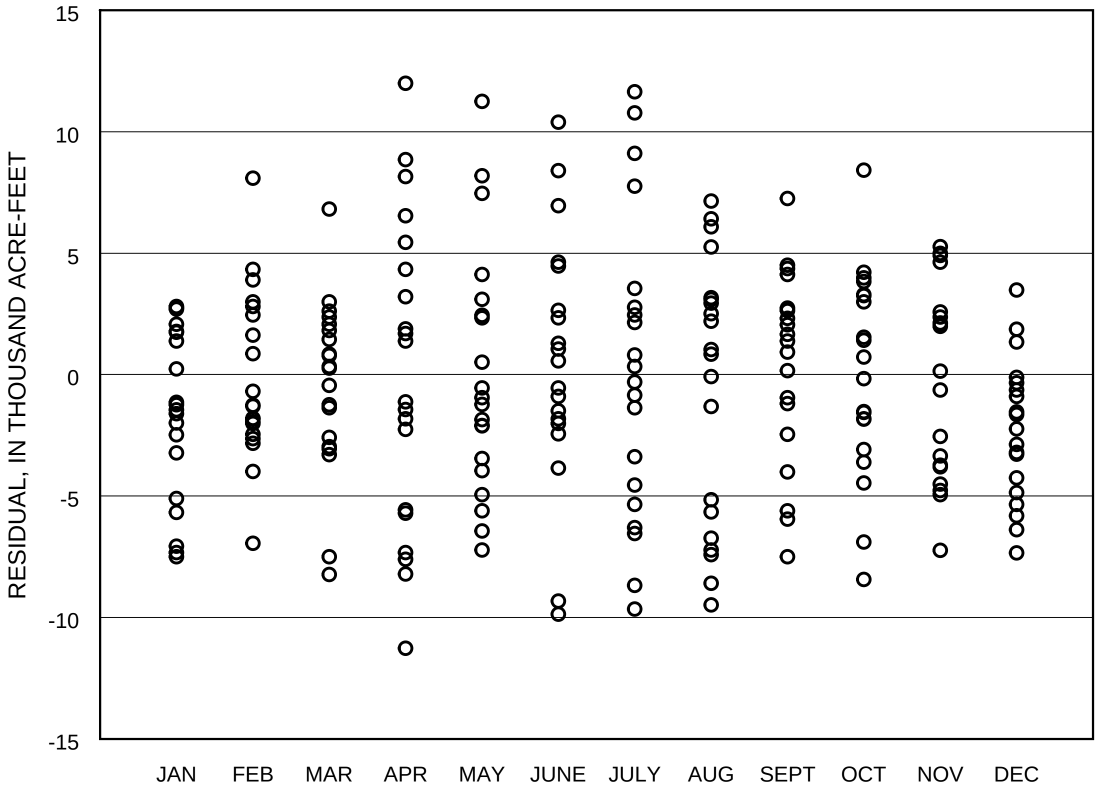

Figure 10. Residuals of estimated monthly changes in volume for Devils Lake for 1980-99 from regression model with monthly coefficients.

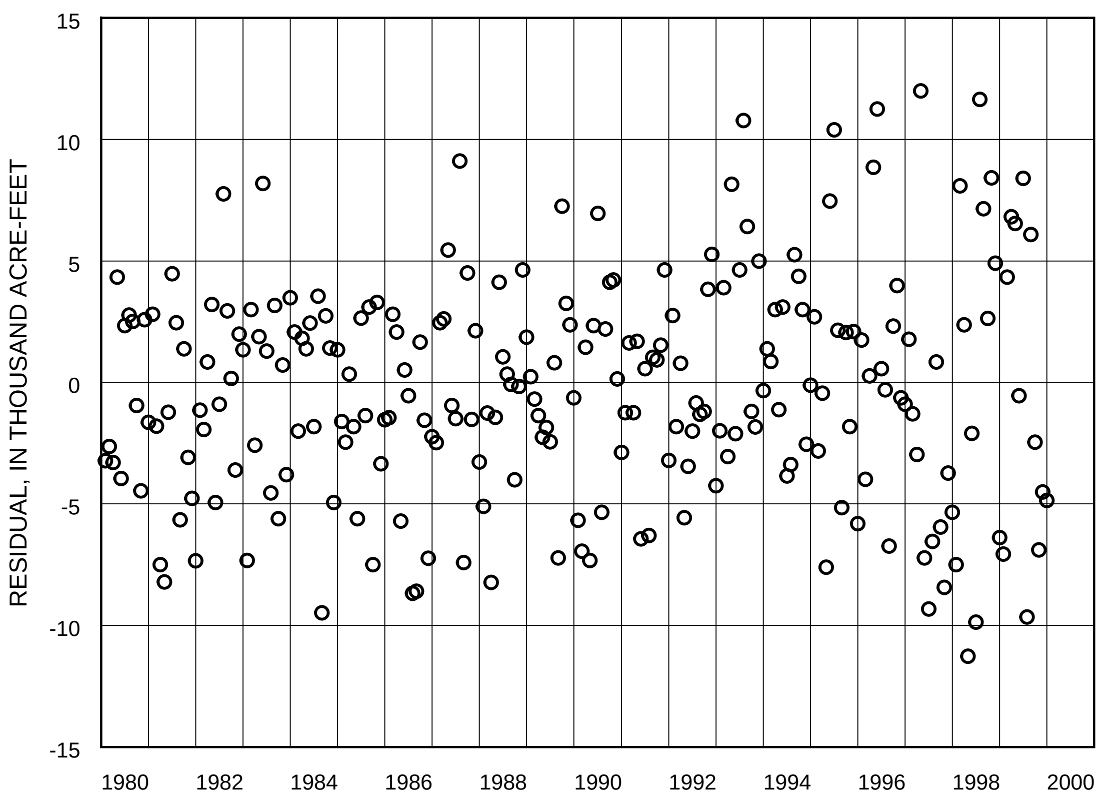

Figure 11. Time series of residuals of estimated monthly changes in volume for Devils Lake for 1980-99 from regression model with monthly coefficients.

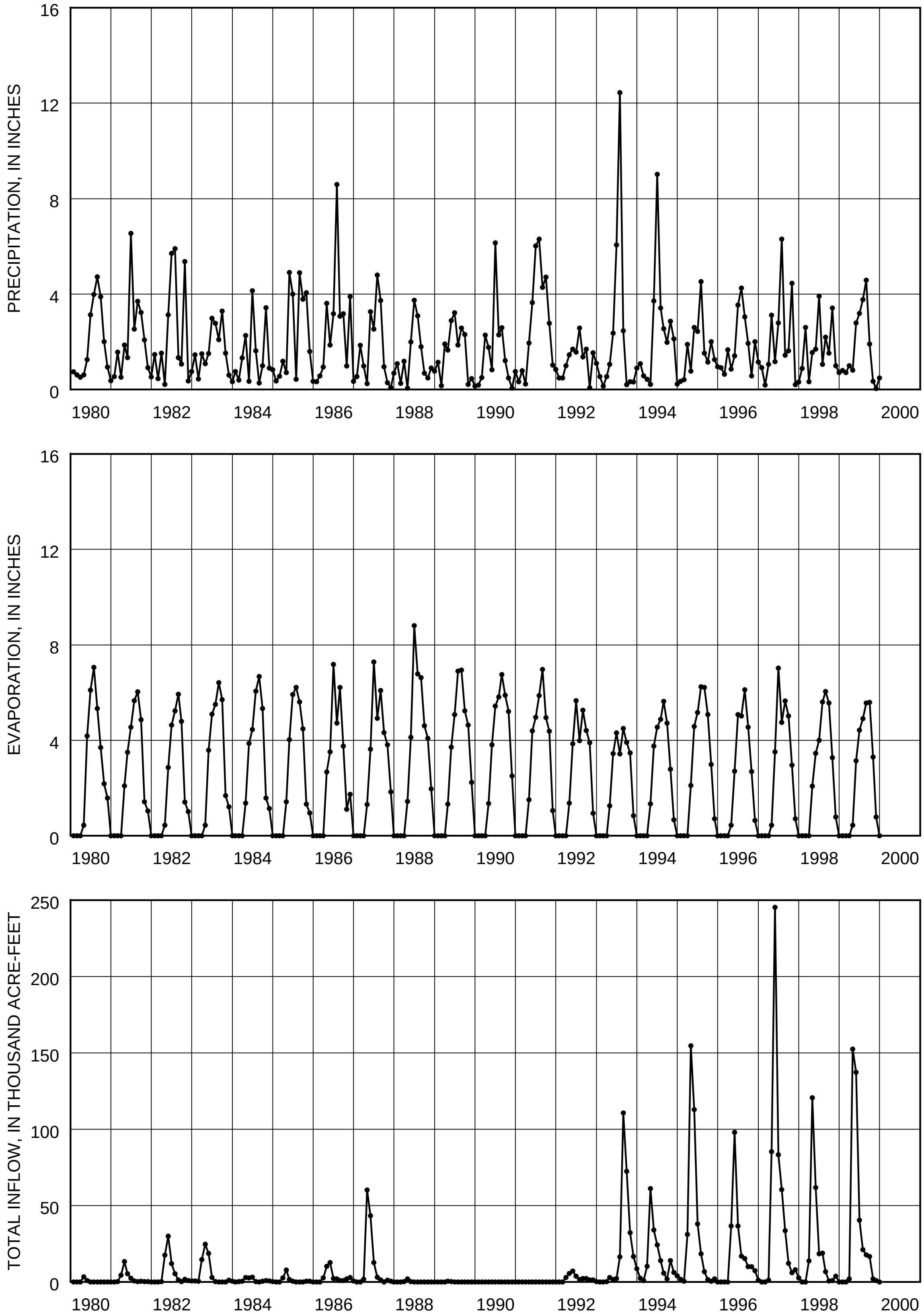

Figure 12. Monthly water-balance data for Devils Lake for 1980-99.

DETAILED WATER AND SULFATE MASS-BALANCE MODELS

At levels greater than 1,425 feet above sea level, Devils Lake consists of a series of interconnected water bodies--West Bay, Main Bay, East Bay, and East Devils Lake (fig. 2)--that have approximately the same water-surface elevation. At levels greater than 1,430 feet above sea level, West Bay begins to expand north through a bridge opening on Highway 19 and includes Pelican Lake. At levels greater than 1,445 feet above sea level, Mikes Lake, Chain Lake, Lake Alice, and Lake Irvine also become part of West Bay. At a level of 1,446.5 feet above sea level, Devils Lake begins to spill through the Jerusalem Outlet into Stump Lake. On August 1, 2001, the level of Devils Lake was 1,448.0 feet above sea level, and flow at gaging station 05056636 (Devils Lake outlet to Stump Lake near Lakota, N. Dak.; site 22, fig. 2) was about 40 cubic feet per second. Devils Lake could continue to rise and eventually fill Stump Lake, and the combined Devils Lake and Stump Lake system could rise and eventually spill from Stump Lake, through Tolna Coulee, to the Sheyenne River. The combined system begins to spill to the Sheyenne River at a level of about 1,459 feet above sea level.

The quality of water in the various bays of Devils Lake differs even when the level of the lake is greater than 1,425 feet above sea level and the lake is a single water body. Detailed spatial water-quality sampling of Devils Lake in 1998 (Sether and others, 1999; Manous, 2000) indicated dissolved ion concentrations were relatively uniform within the bays but large differences existed among the bays. The uniform concentrations probably were caused by efficient wind-induced mixing within the bays, and the differences were caused by restricted openings between the bays. Recorded dissolved sulfate concentrations for 1988-2000 (fig. 13) for West Bay, Main Bay, East Bay, East Devils Lake, and Stump Lake (sites 17, 18, 20, 21, and 23, respectively; fig. 2) indicate that large increases in sulfate concentration existed from Main Bay to East Bay and from East Bay to East Devils Lake even during the high lake levels of the late 1990’s. The concentrations were relatively stable from 1988 to 1992, a period of generally falling lake levels (fig. 3), but declined steadily from 1993 to 1998, a period of generally increasing lake levels. The concentrations remained relatively stable after 1998. Stump Lake was not connected to Devils Lake during the 1990’s, and the rapid decrease in sulfate concentrations shown in figure 13 resulted from local inflow to Stump Lake.

To simulate the future operation and water-quality effects of an outlet from Devils Lake, the processes that control the sulfate concentrations and the concentrations of other chemical constituents in Devils Lake and Stump Lake needed to be determined. Therefore, detailed water and sulfate mass-balance models were developed for Devils Lake and Stump Lake. A schematic of the models is shown in figure 14. The models were used to compute the changes in volume and the changes in sulfate load for each of six major storage compartments--West Bay North (which includes Pelican Lake and the upstream chain of lakes as indicated previously), West Bay South, Main Bay, East Bay, East Devils Lake, and Stump Lake--in response to precipitation, evaporation, inflow, and outflow from each compartment. The storage compartments are referred to as lake “boxes.” The algorithms and assumptions used to compute the natural (without a constructed outlet) mass balance are described in the remainder of this section, and the various outlet alternatives and the Channel A diversion shown in figure 14 will be discussed in a later section.

Water Mass-Balance Computation

Monthly water-balance data for 1980-99 were used as the starting point to develop the following detailed monthly water mass-balance equations for the lake boxes:

$$V_0(t) = V_0(t-1) + \frac{1}{12}[P(t) - E(t)]A_0(t-1) + Q_B(t) - Q_{01}(t) \qquad (4)$$

$$V_1(t) = V_1(t-1) + \frac{1}{12}[P(t) - E(t)]A_1(t-1) + 0.3U(t) + Q_{01}(t) - Q_{12}(t) \qquad (5)$$

$$V_2(t) = V_2(t-1) + \frac{1}{12}[P(t) - E(t)]A_2(t-1) + Q_A(t) + 0.3U(t) + Q_{12}(t) - Q_{23}(t) \qquad (6)$$

$$V_3(t) = V_3(t-1) + \frac{1}{12}[P(t) - E(t)]A_3(t-1) + 0.3U(t) + Q_{23}(t) - Q_{34}(t) \qquad (7)$$

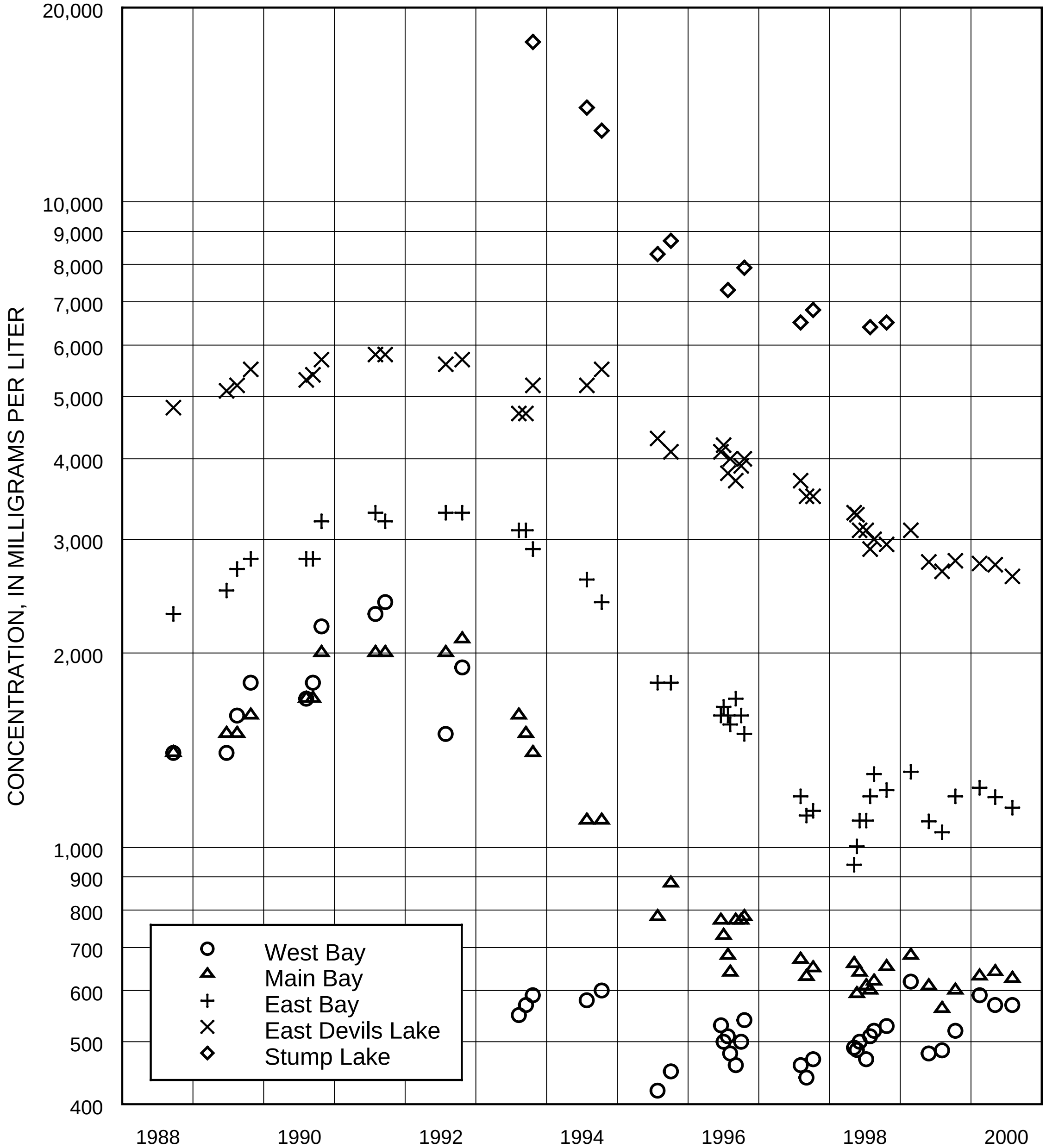

Figure 13. Recorded dissolved sulfate concentrations for Devils Lake and Stump Lake for 1988-2000.

$$V_4(t) = V_4(t-1) + \frac{1}{12}[P(t) - E(t)]A_4(t-1) + 0.1U(t) + Q_{34}(t) - Q_{45}(t) \tag{8}$$

$$V_5(t) = V_5(t-1) + \frac{1}{12}[P(t) - E(t)]A_5(t-1) + Q_S(t) + Q_{45}(t) - Q_N(t) \tag{9}$$

where

$V_i(t)$ is the volume of the ith lake box at the end of month t, in acre-feet [boxes refer to West Bay North (i = 0), West Bay South (i =1), Main Bay (i = 2), East Bay (i = 3), East Devils Lake (i = 4), and Stump Lake (i = 5)];

$A_i(t)$ is the surface area of the ith lake box at the end of month t, in acres;

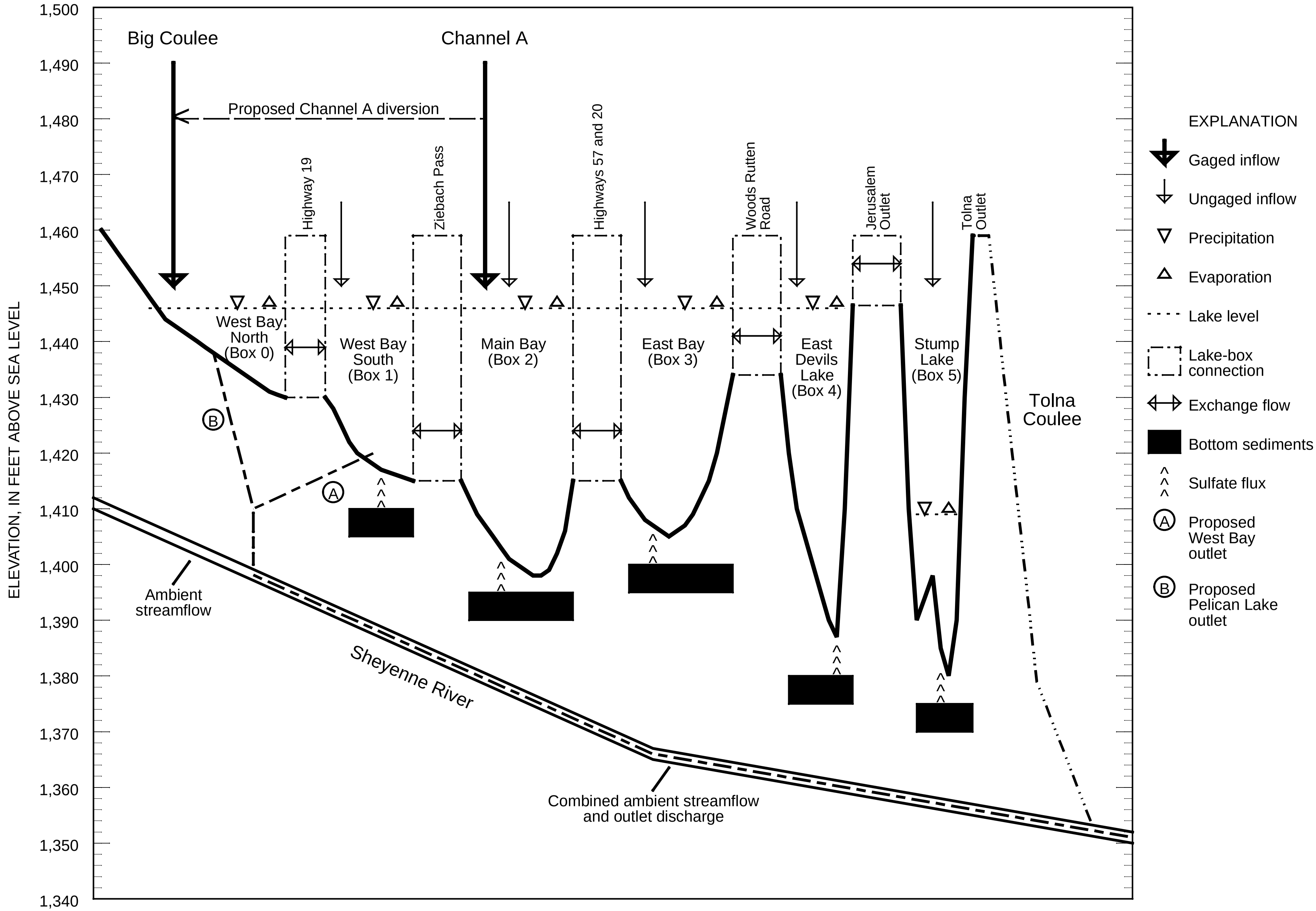

Figure 14. Schematic of Devils Lake water and sulfate mass-balance models. (Horizontal axis and elevation of Sheyenne River not to scale. Lake level shown is for October 1, 2000. Bottom elevations of lake-box connections are for October 1, 2000.)

$Q_B(t)$ is inflow from Big Coulee in month t, in acre-feet;

$Q_{ij}(t)$ is flow from lake box i to lake box j in month t, in acre-feet;

$U(t)$ is total ungaged inflow in month t, in acre-feet;

$Q_A(t)$ is inflow from Channel A in month t, in acre-feet;

$Q_S(t)$ is local inflow to Stump Lake in month t, in acre-feet; and

$Q_N(t)$ is flow from the natural outlet from Stump Lake to Tolna Coulee in month t, in acre-feet.

If $Q_{45}(t) = 0$, which was the case for 1980-99, the first five equations (eqs. 4 through 8) add up to the overall water mass-balance equation for Devils Lake. The coefficients for ungaged inflow in equations 5 through 8 indicate 30 percent of the ungaged inflow entered each of boxes 1, 2, and 3 (West Bay South, Main Bay, and East Bay) and 10 percent of the ungaged inflow entered box 4 (East Devils Lake). Because ungaged inflow is a small component of the overall water balance, the distribution of the ungaged inflow among the boxes did not significantly affect the sulfate concentrations of the water. Approximate estimates of contributing drainage areas adjacent to the lake, based on topographic maps from the Devils Lake Basin, indicated that the distribution of ungaged inflow among the lake boxes represented by equations 5 through 8 was reasonable. The flow of water between the boxes (the Q_{ij}'s) and the local inflow to Stump Lake were calculated as described in appendix A. These flows did not include wind- or buoyancy-induced exchange flows, which are considered in a later section.

During rapid lake-level rises, such as during 1993-99, inflow and outflow for the lake boxes were the dominant components of the water balance. Inflow and outflow for each box for 1992-99 are shown in figure 15. From 1992 through mid-1994 when the level of Devils Lake was less than 1,430 feet above sea level, inflow to box 0 (West Bay North) was equal to outflow from box 0 because box 0 was empty. As the level of Devils Lake rose from less than 1,430 feet above sea level in June 1994 to 1,447 feet above sea level in 1999, box 0 began to fill and outflow was less than inflow. Inflow to box 1 (West Bay South) was slightly higher than outflow from box 0 because of ungaged inflow to box 1, and outflow from box 1 was much less than inflow, indicating large increases in storage in box 1 during 1993-99. Inflow to box 2 (Main Bay) was higher than inflow to any of the other boxes because of large contributions from both West Bay South and Channel A, and a large amount of the inflow remained in box 2 in the form of increased storage. Box 3 (East Bay) received a significant amount of inflow from box 2, and most of the inflow remained in box 3 in the form of increased storage. Because box 4 (East Devils Lake) and box 5 (Stump Lake) were much smaller in surface area and had less available storage than the other boxes during 1992-99, those boxes received much less inflow than the other boxes. East Devils Lake and Stump Lake were below their spill elevations during 1992-99 and, thus, no outflow occurred from either of those boxes during that period.

Precipitation and evaporation for each lake box for 1992-99 are shown in figure 16. Box 0 had no precipitation or evaporation during 1992-94 (because the box was empty), but both volumes increased rapidly during 1995-99 because of large surface-area increases. In 1999, the surface area of box 0 was larger than the surface area of any of the other boxes. During 1993-99, precipitation and evaporation for the other lake boxes also increased because of larger surface areas, but the increases were much smaller than those for box 0. For all boxes, annual evaporation losses were higher than annual precipitation gains, indicating a net loss of water to the atmosphere.

Monthly changes in volume for each lake box for 1992-99 are shown in figure 17. With the exception of the summer flood of 1993, large increases occurred during the spring melt, and decreases occurred during the summer. However, small increases also occurred during the fall and winter because precipitation gains and small amounts of inflow during those months outweighed evaporation losses. The changes in volume for boxes 1, 2, and 3 were similar for 1995-99 because the surface areas of those boxes were similar during that period. Boxes 4 and 5 had much smaller surface areas and, thus, much smaller (in absolute value) changes in volume than the other boxes. The surface area of box 0 increased rapidly during 1997-99, and the resulting change in volume became an important factor in the overall water balance for Devils Lake. If Devils Lake continues to rise to its natural spill elevation (1,459 feet above sea level), the surface area of box 0 will be larger than the surface area of all other boxes combined (see appendix A).

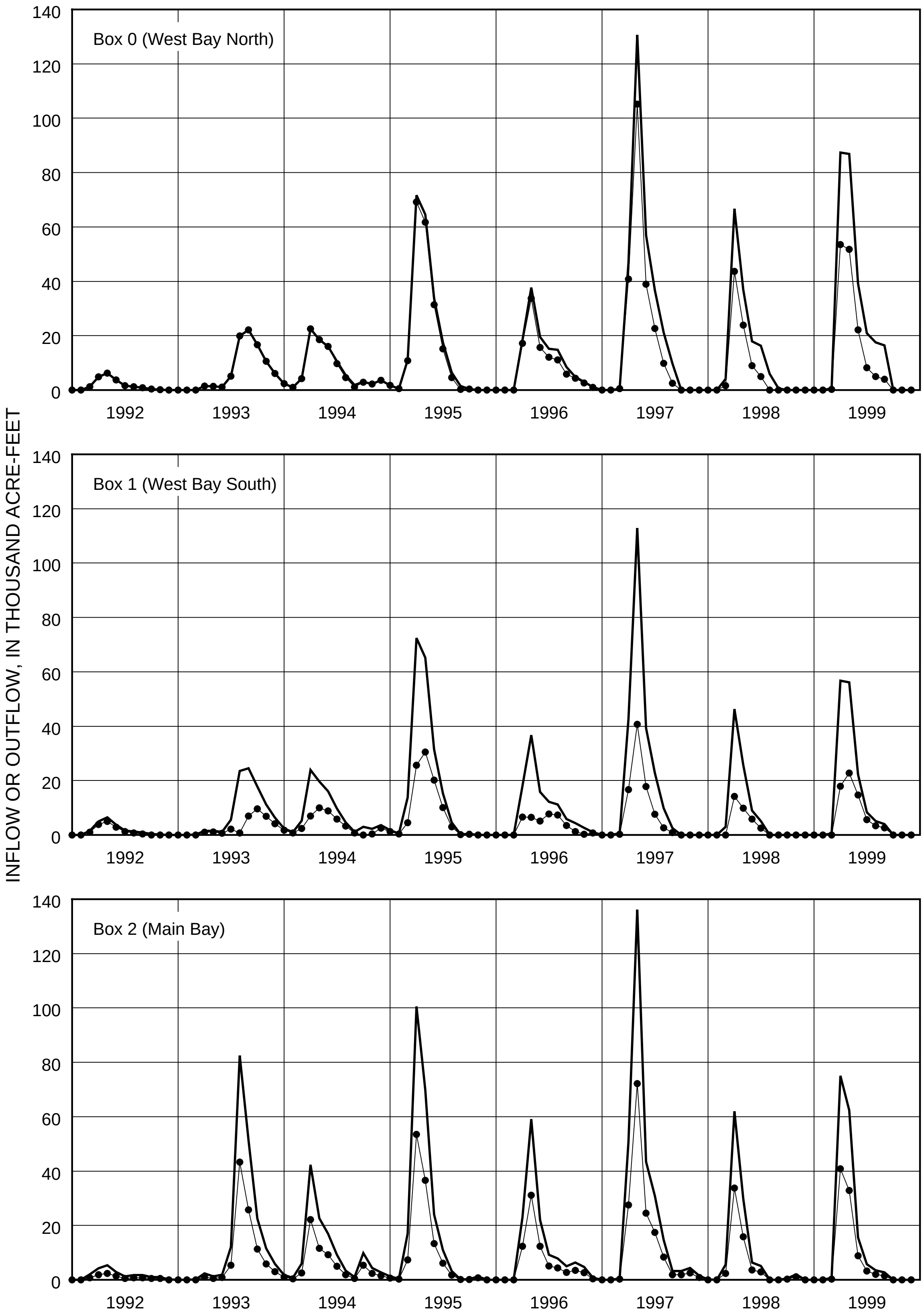

Figure 15. Monthly inflow and outflow for lake boxes for 1992-99. (Solid line indicates inflow, and dotted line indicates outflow.)

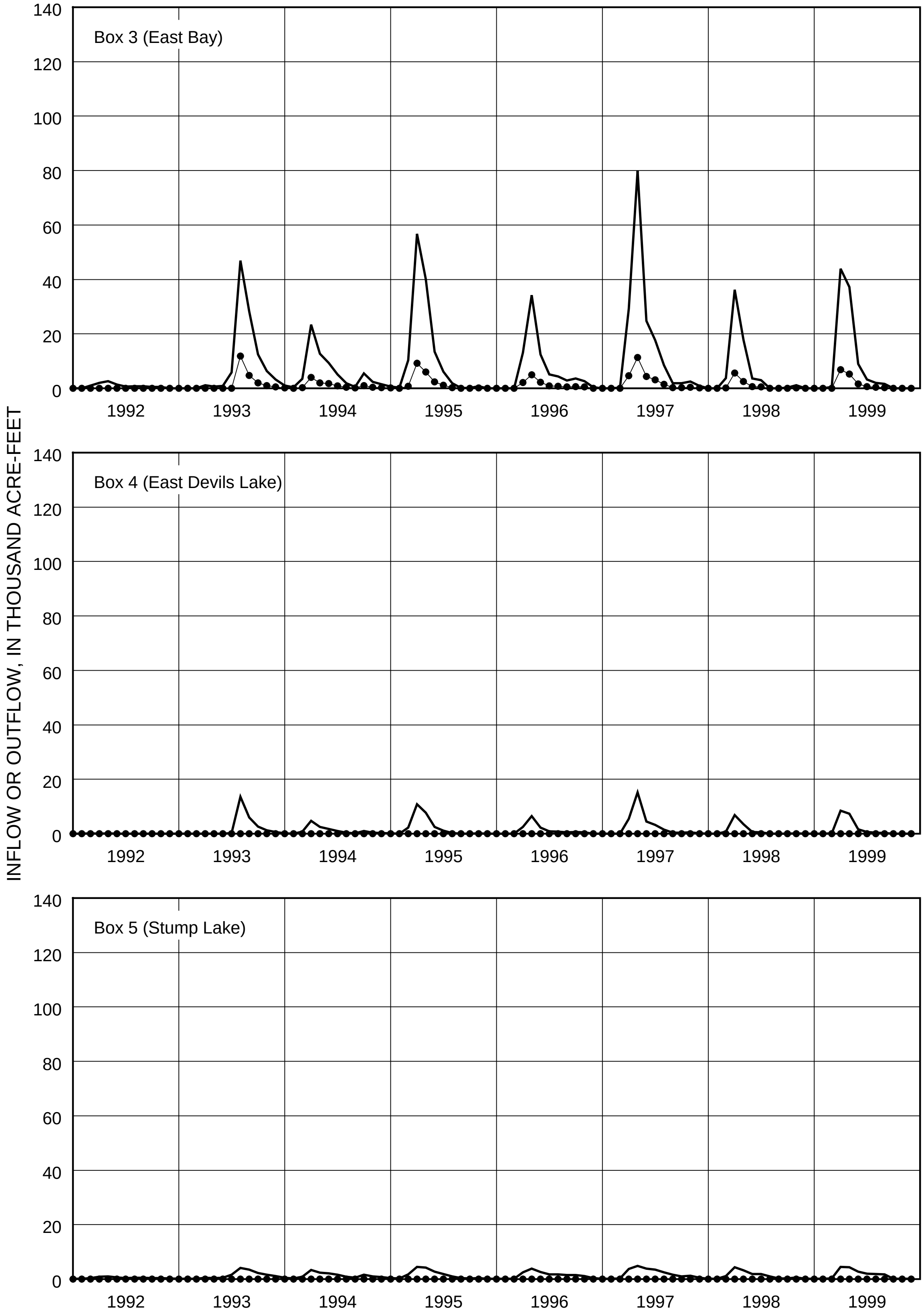

Figure 15. Monthly inflow and outflow for lake boxes for 1992-99--Continued. (Solid line indicates inflow, and dotted line indicates outflow.)

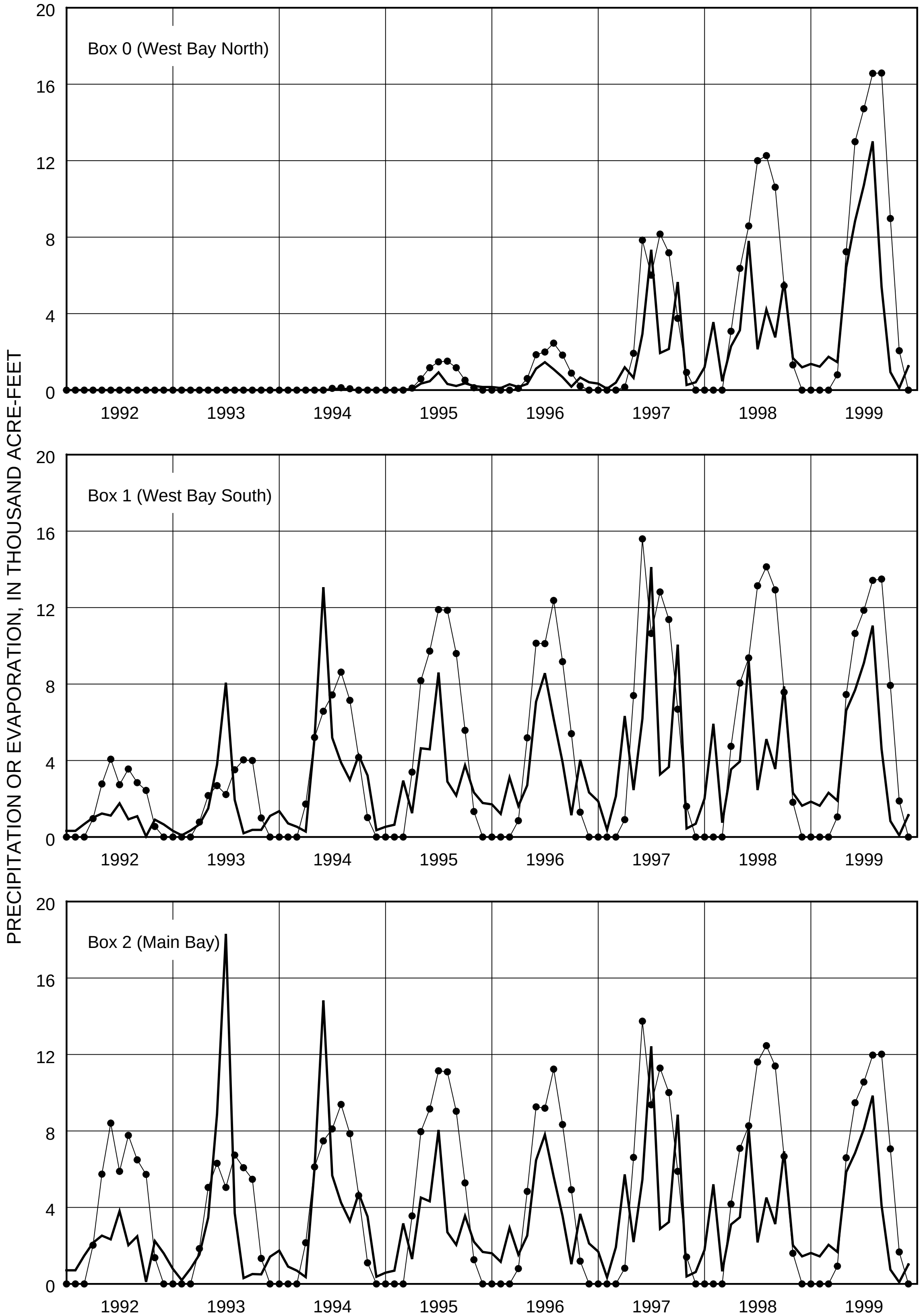

Figure 16. Monthly precipitation and evaporation for lake boxes for 1992-99. (Solid line indicates precipitation, and dotted line indicates evaporation.)

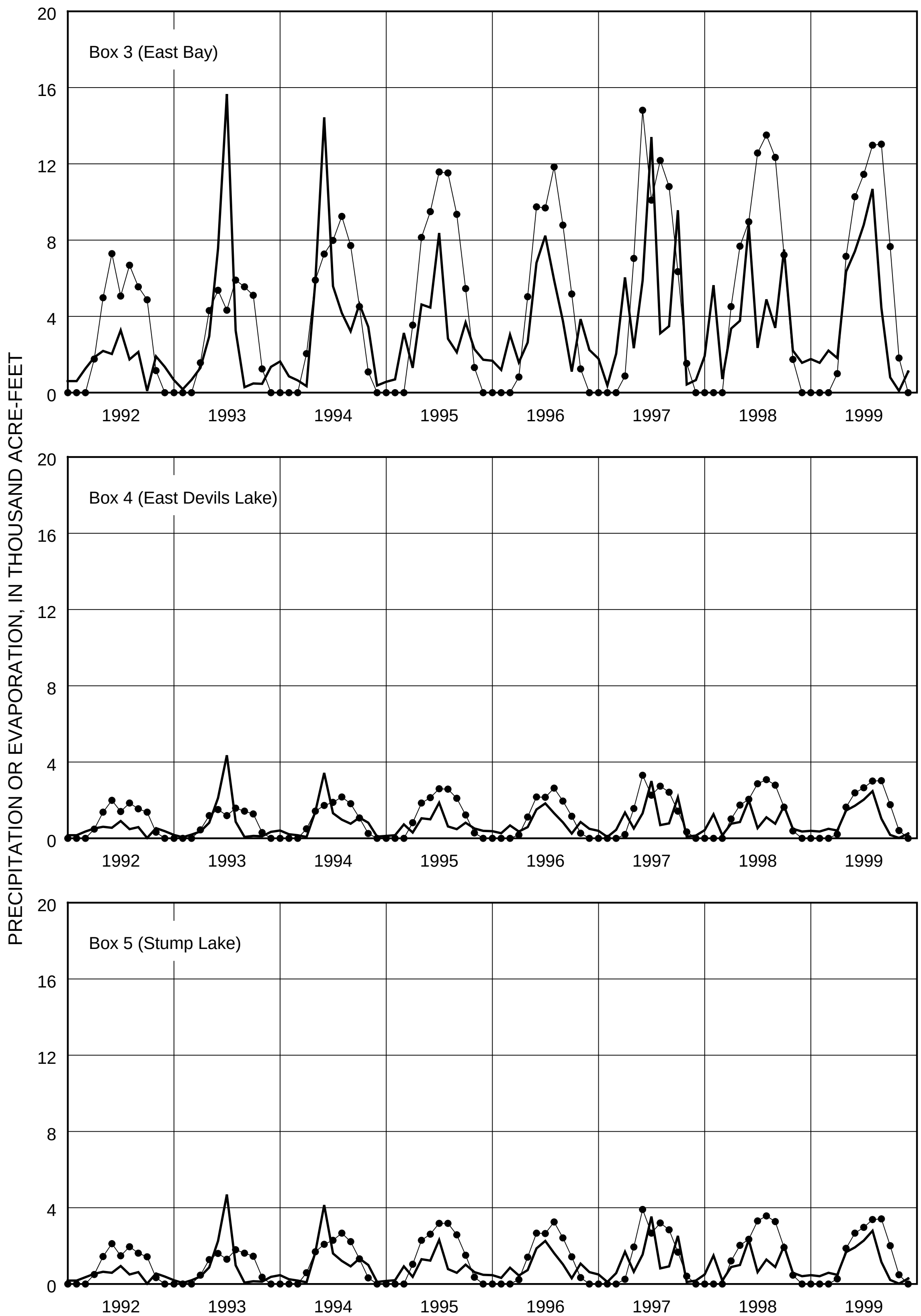

Figure 16. Monthly precipitation and evaporation for lake boxes for 1992-99--Continued. (Solid line indicates precipitation, and dotted line indicates evaporation.)

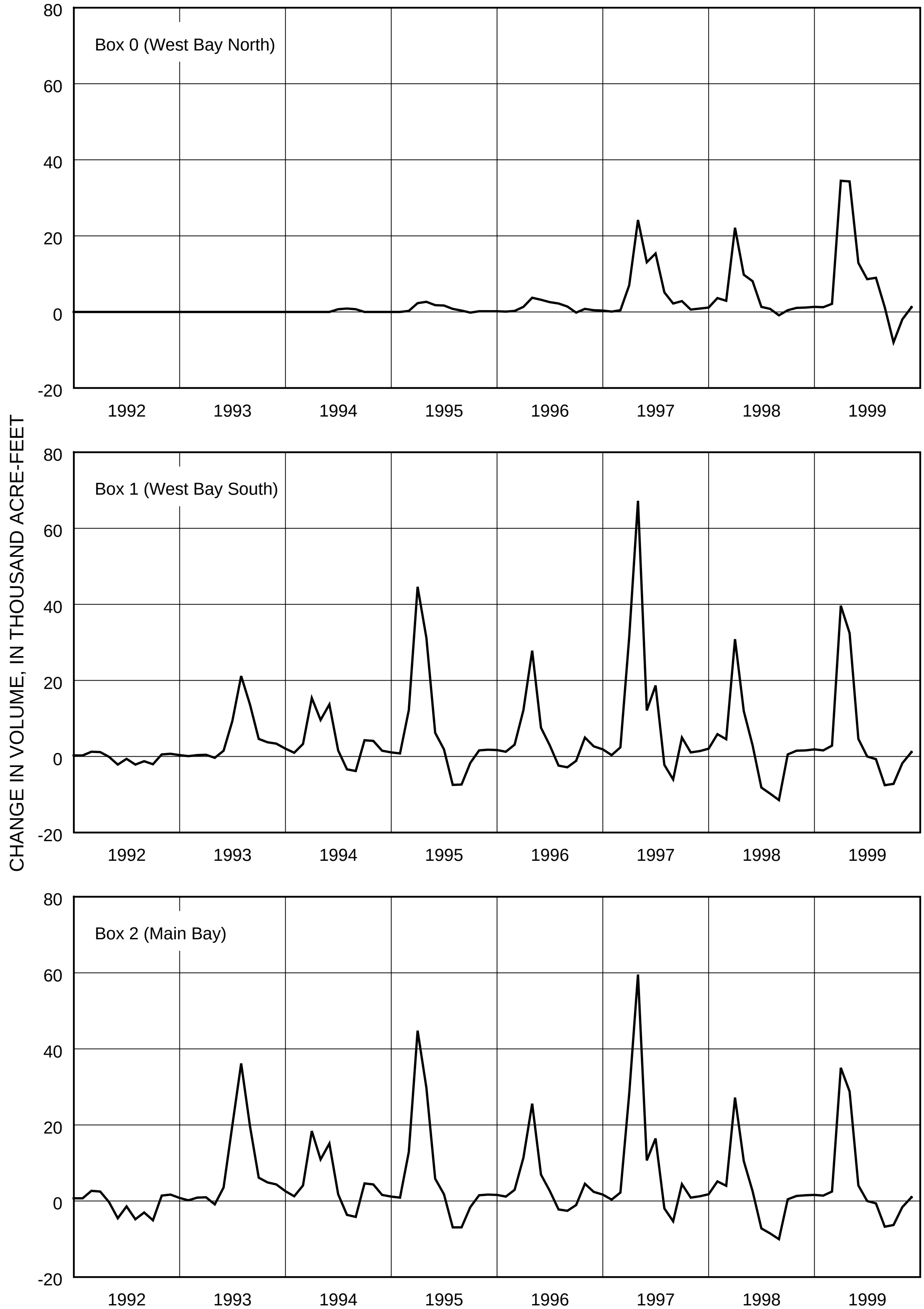

Figure 17. Monthly changes in volume for lake boxes for 1992-99.

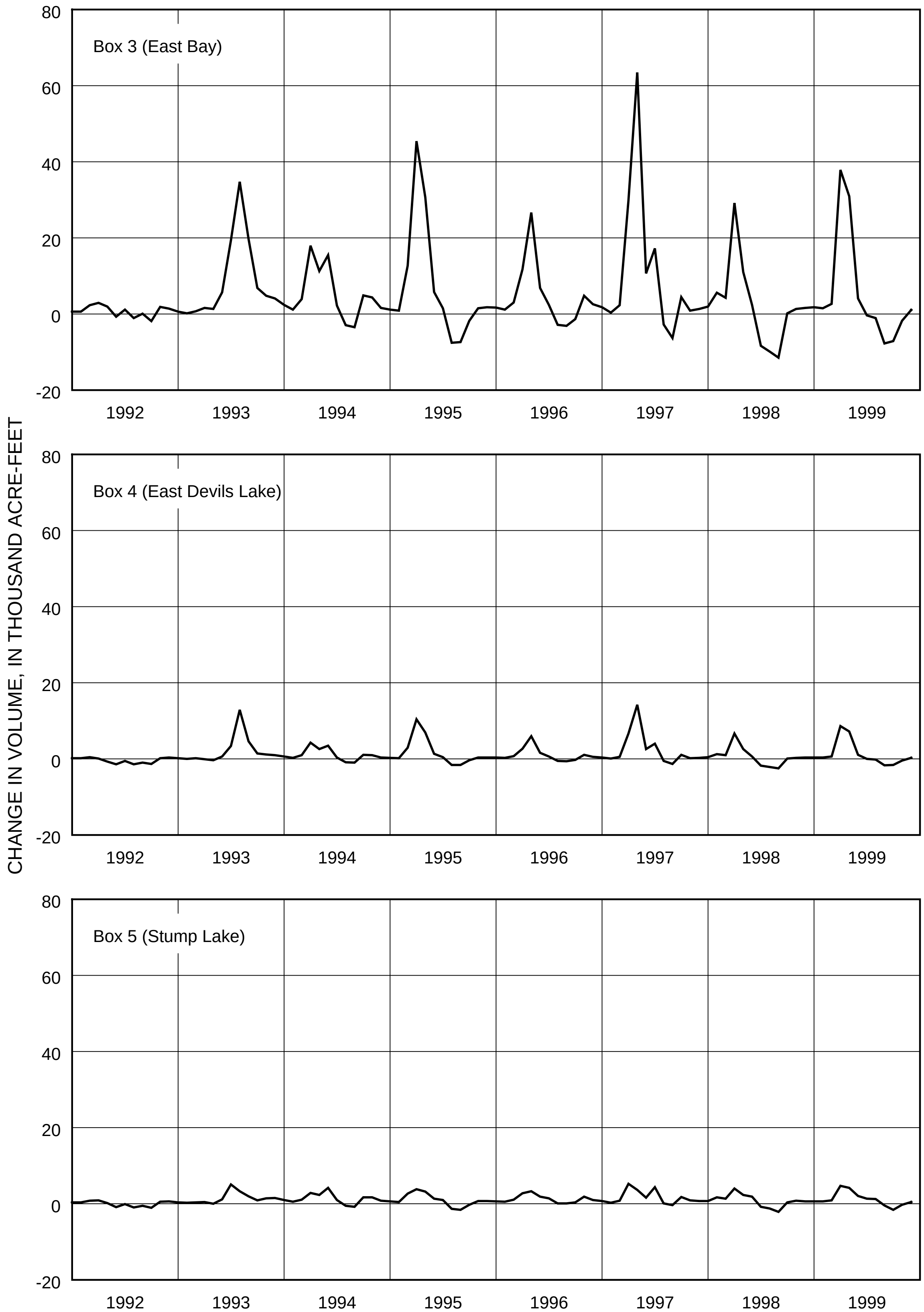

Figure 17. Monthly changes in volume for lake boxes for 1992-99--Continued.

Sulfate Mass-Balance Computation

The change in sulfate load for each lake box for a given month depends on the sulfate concentrations in the inflows and outflows for each box and the flux of sulfate from bottom sediments. Because detailed spatial and temporal water-quality data for Devils Lake and Stump Lake for 1980-99 are unavailable, simplifying assumptions were required to approximate the concentrations in the inflows and outflows and to approximate the total sulfate load for each box. One simplifying assumption that was used for model development is that the sulfate concentration in each box was spatially homogeneous--that is, the sulfate concentration of a given box at any given time was uniform with depth and location. As indicated previously, because of efficient wind-induced mixing within bays, this was a reasonable assumption. Another assumption that was used is that sulfate was a conservative constituent--that is, no biogeochemical reactions existed that caused long-term changes in the sulfate load. Although biogeochemical reactions probably affect the sulfate mass balance on a seasonal time scale, they probably are not significant on a long-term scale (Robert Lent, U.S. Geological Survey, oral commun., 2001). The results of this section confirm that most of the interannual variation in sulfate concentrations can be explained by conservative movement of sulfate between boxes and between the bottom sediments and water column.

Sulfate mass-balance equations first were developed using the assumptions that no interaction occurred between the bottom sediments and the water column and that no wind- or buoyancy-induced mixing occurred between lake boxes. These assumptions served as a starting point to calculate the sulfate mass balance. A component then was added to the mass-balance equations to account for flux of sulfate between sediment pore water and the boxes. The addition of the component improved the overall sulfate mass balance for the entire lake but did not provide a good representation of the sulfate concentration in each box. A second component then was added to the equations to account for mixing between boxes. The model that included both components provided a good fit to recorded concentrations.

Sulfate Mass-Balance Model With No Sediment Interaction and No Mixing Between Lake Boxes

In the simplified sulfate mass-balance model, the only external sulfate loads entering the lake boxes were from Big Coulee, Channel A, and ungaged inflow. To determine the sulfate mass balance for Devils Lake, unbiased estimates of these external loads were needed for each month. The unbiased estimates were determined using the rating curve method described by Cohn and others (1989) in which a regression model is used to fit a relation between sulfate concentration and daily discharge. The regression model was used along with a bias correction factor to determine the unbiased estimates of monthly loads.

The fitted regression model that relates sulfate concentration to daily discharge for Big Coulee is given by

$$\log(C) = T(\tau) - [0.114 - 0.015\cos(2\pi\tau) - 0.022\sin(2\pi\tau)]\log(X+1) + e \qquad (10)$$

where

log is the base-10 logarithm;

C is the sulfate concentration for Big Coulee, in milligrams per liter;

$T(\tau)$ is a temporal trend in concentration;

τ is the time index, in decimal water years[2];

$\cos(a)$ is the cosine of angle a, where a is in radians;

$\sin(a)$ is the sine of angle a, where a is in radians;

[2] In U.S. Geological Survey reports, water year is the 12-month period, October 1 through September 30. The water year is designated by the calendar year in which it ends; thus, the water year ending September 30, 2001, is called "water year 2001."

X is the mean daily discharge from Big Coulee, in cubic feet per second; and

e is the random error.

The regression model relates a concentration measurement (C) on a given day to mean daily discharge (X). The coefficients given in equation 10 were estimated using ordinary least-squares regression and recorded sulfate concentrations for 1983-99 (fig. 18). No recorded sulfate concentrations are available for 1990-91 because Big Coulee was dry in those years. The coefficient of determination (R^2) for equation 10 was 87 percent, and the standard error was 0.0803 in logarithmic units. Standard residual diagnostics indicated the regression model provided a good fit to recorded concentrations.

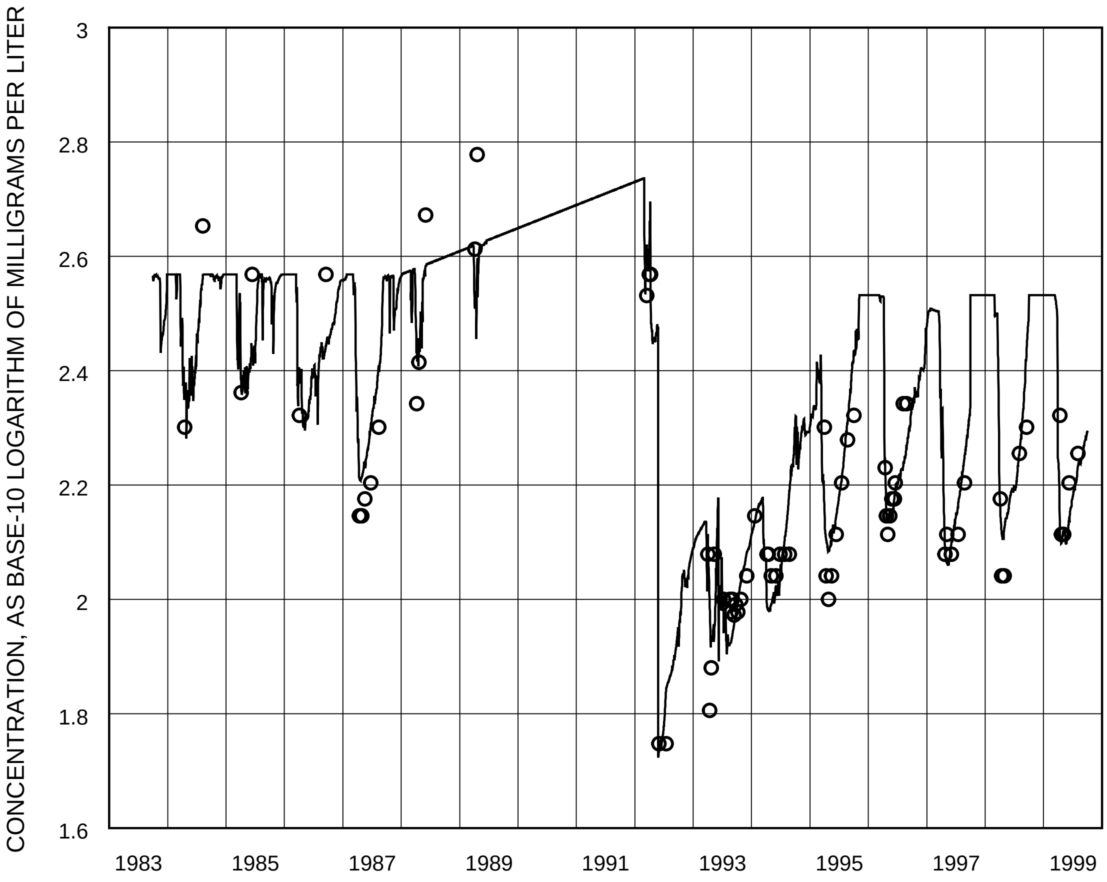

Figure 18. Recorded and fitted dissolved sulfate concentrations for Big Coulee for 1983-99 from regression model. (Points indicate recorded concentrations, and line indicates fitted concentrations.)

The time index (τ) given in equation 10 was used to assign a decimal water year to each concentration. For example, τ = 1,992.0 corresponded to October 1, 1991 (the first day of water year 1992), τ = 1,992.25 corresponded to January 1, 1992, etc. The relation between concentration and discharge changed with season because of the cosine and sine terms. The temporal trends in concentration were denoted by:

$T(\tau) = 2.568$ for $\tau < 1{,}988.25$;

$T(\tau) = 2.568 + 0.041(\tau - 1{,}988.25)$ for $1{,}988.25 < \tau < 1{,}992.65$;

$T(\tau) = 1.972 + 0.180(\tau - 1{,}992.65)$ for $1{,}992.65 < \tau < 1{,}995.65$; and

$$T(\tau) = 2.512 \text{ for } \tau > 1{,}995.65 .$$

The trends were significant and consisted of an increase in concentration from early 1988 to mid-1992, a rapid decrease in concentration in mid-1992, and another increase from mid-1992 to mid-1995 (fig. 18). The cause of the trends is unknown, but they probably are related to sulfate storage in the upstream chain of lakes and in small lakes, wetlands, and soils in the upper Devils Lake Basin and to variations in the contributing drainage area. The increase from early 1988 to mid-1992 coincided with the onset of drought conditions and may have resulted from increased concentrations in upper basin water bodies. Inflows to these water bodies during the drought were not sufficient to dilute sulfate that remained from previous years. The rapid decrease in mid-1992 followed the very wet summer and fall of 1991 when the upper basin water bodies received freshwater inflow but Devils Lake received very little inflow. Spring runoff was high in 1992 compared to spring runoff in previous years and Devils Lake received considerable inflow during that time, but sulfate concentrations for Big Coulee were much lower in 1992 than during the mid-1980’s before the drought. Evidently, areas of the basin that contributed flow during 1991 and 1992 were low in soluble salts. The concentrations increased from mid-1992 to mid-1995 and then stabilized at levels somewhat lower than those before the drought.

The estimated monthly sulfate loads for Big Coulee for 1984-99 are shown in figure 19. The estimates of log-transformed daily sulfate concentrations generated using equation 10 were back-transformed, and the smearing technique

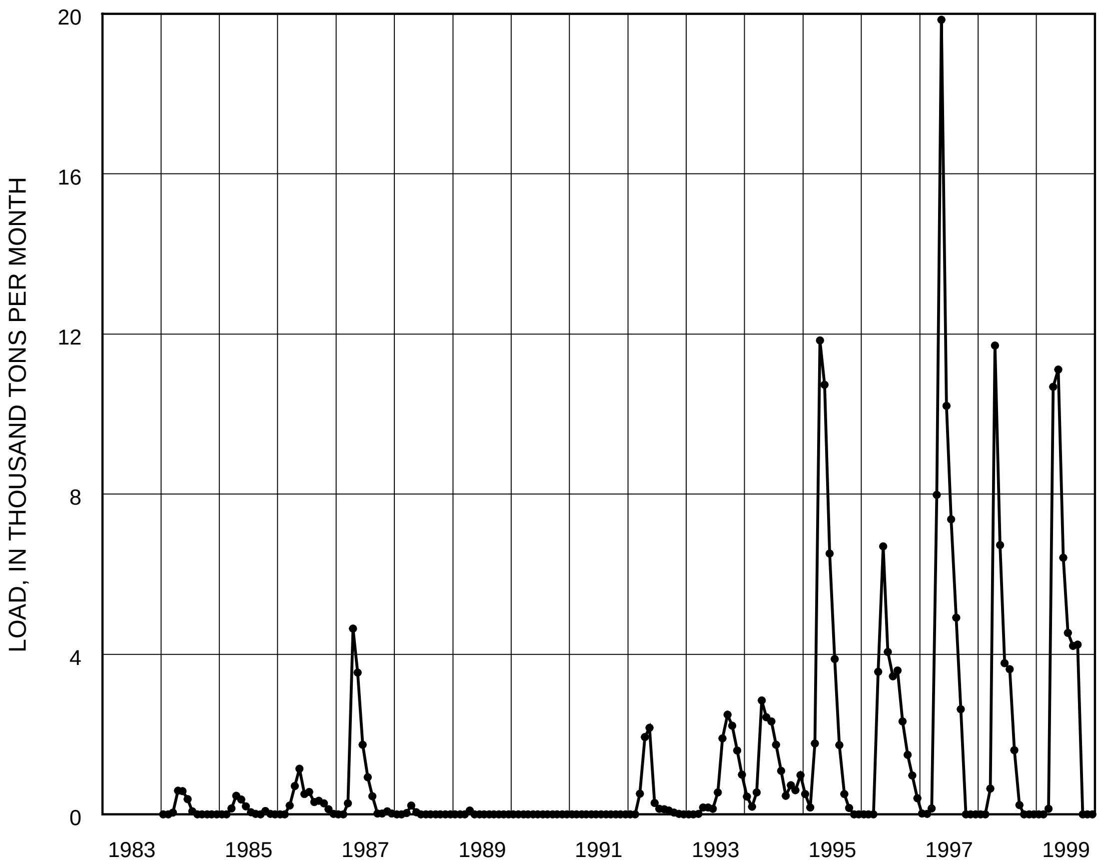

Figure 19. Estimated monthly dissolved sulfate loads for Big Coulee for 1984-99.

(Gilroy and others, 1990) was used to correct for transformation bias. The bias-correction factor obtained using the smearing technique was 1.016, so back-transformed sulfate concentrations were increased by 1.6 percent before being used to compute the monthly loads. The potential differences between the estimated monthly loads and the actual monthly loads were small enough to disregard in the overall sulfate mass balance for Devils Lake.

The fitted regression model that relates sulfate concentration to daily discharge for Channel A is similar in form to equation 10 and is given by

$$\log(C) = T(\tau) - [0.174 + 0.042\cos(2\pi\tau) - 0.021\sin(2\pi\tau)]\log(X+1) + e \qquad (11)$$

where

$T(\tau) = 2.586$ for $\tau < 1{,}988.25$;

$T(\tau) = 2.586 + 0.054(\tau - 1{,}988.25)$ for $1{,}988.25 < \tau < 1{,}992.65$;

$T(\tau) = 2.329 + 0.095(\tau - 1{,}992.65)$ for $1{,}992.65 < \tau < 1{,}995.65$; and

$T(\tau) = 2.614$ for $\tau > 1{,}995.65$.

The recorded and fitted sulfate concentrations for Channel A for 1983-99 are shown in figure 20. The coefficient of determination for equation 11 was 72 percent, and the standard error was 0.161 in logarithmic units. Standard residual

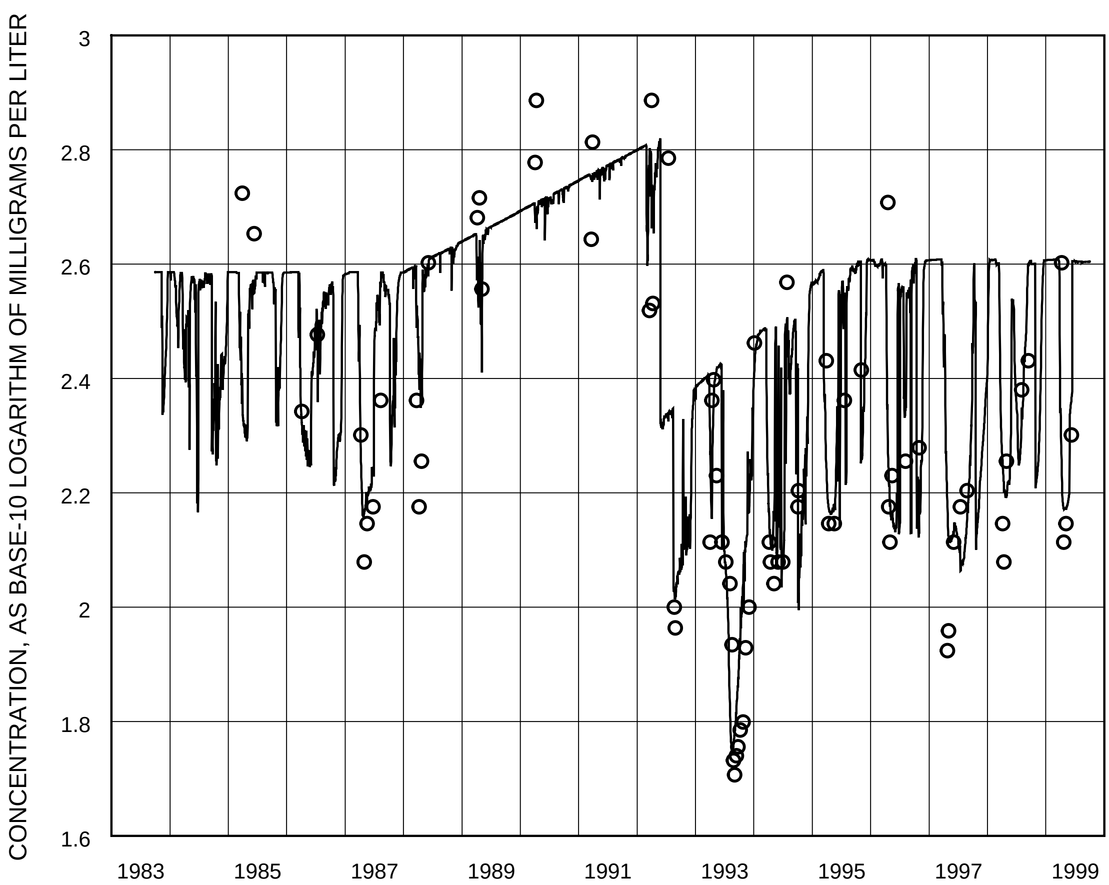

Figure 20. Recorded and fitted dissolved sulfate concentrations for Channel A for 1983-99 from regression model. (Points indicate recorded concentrations, and line indicates fitted concentrations.)

diagnostics indicated the regression model provided a good fit to recorded concentrations. The temporal trends were similar to those for Big Coulee (fig. 18) except that concentrations during 1995-99 were slightly higher (for the same discharge) than those before the drought and the decrease during 1992 was not as severe as the decrease for Big Coulee. The bias-correction factor obtained using the smearing technique was 1.071, so back-transformed daily sulfate concentrations were increased by 7.1 percent before being used to compute monthly loads. The resulting estimated monthly sulfate loads (fig. 21) were comparable to those for Big Coulee (fig. 19) although Channel A provided somewhat higher loads than Big Coulee during some months and somewhat lower loads than Big Coulee during other months.

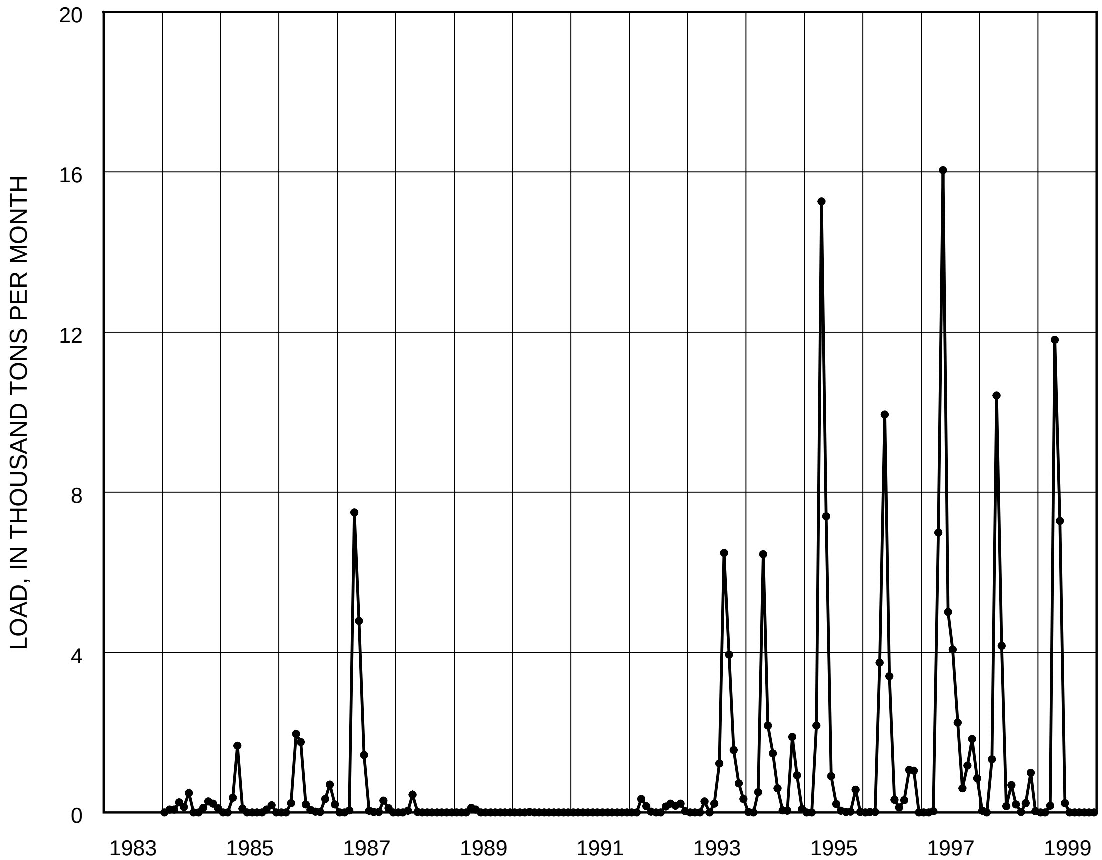

Figure 21. Estimated monthly dissolved sulfate loads for Channel A for 1984-99.

The estimated monthly sulfate loads for Big Coulee and Channel A were used to assign effective monthly sulfate concentrations to inflows from Big Coulee and Channel A using the following equation:

$$C_B(t) = \frac{L_B(t)}{Q_B(t)} \text{ and } C_A(t) = \frac{L_A(t)}{Q_A(t)} \tag{12}$$

where

$C_B(t)$ is the effective monthly sulfate concentration for Big Coulee, in tons per acre-foot;

$L_B(t)$ is the estimated monthly sulfate load for Big Coulee, in tons;

$C_A(t)$ is the effective monthly sulfate concentration for Channel A, in tons per acre-foot; and

$L_A(t)$ is the estimated monthly sulfate load for Channel A, in tons.

The effective monthly sulfate concentrations for ungaged inflow could not be obtained by direct application of the rating curve method because no concentration or daily-flow data exist for ungaged inflow. Therefore, the effective concentration for ungaged inflow to each bay was assumed to be the same as the effective concentration for Channel A. Because ungaged inflow is a small component of total inflow, this assumption should not have a significant effect on the overall sulfate mass balance.

The effective monthly sulfate concentrations for inflow, a sulfate concentration of 0.83 milligram per liter (0.00113 tons per acre-foot) for precipitation (W.R. Berkas, U.S. Geological Survey, oral commun., 2001), and the water-balance equations (eqs. 4 through 9) were used to obtain the following combined sulfate mass-balance equations for the lake boxes:

$$S_0(t) = S_0(t-1) + \frac{0.00113}{12}P(t)A_0(t-1) + Q_B(t)C_B(t) - Q_{01}(t)C_{01}(t) \tag{13}$$

$$S_1(t) = S_1(t-1) + \frac{0.00113}{12}P(t)A_1(t-1) + 0.3U(t)C_A(t) + Q_{01}(t)C_{01}(t) - Q_{12}(t)C_{12}(t) \tag{14}$$

$$S_2(t) = S_2(t-1) + \frac{0.00113}{12}P(t)A_2(t-1) + [Q_A(t) + 0.3U(t)]C_A(t) + Q_{12}(t)C_{12}(t) - Q_{23}(t)C_{23}(t) \tag{15}$$

$$S_3(t) = S_3(t-1) + \frac{0.00113}{12}P(t)A_3(t-1) + 0.3U(t)C_A(t) + Q_{23}(t)C_{23}(t) - Q_{34}(t)C_{34}(t) \tag{16}$$

$$S_4(t) = S_4(t-1) + \frac{0.00113}{12}P(t)A_4(t-1) + 0.1U(t)C_A(t) + Q_{34}(t)C_{34}(t) - Q_{45}(t)C_{45}(t) \tag{17}$$

$$S_5(t) = S_5(t-1) + \frac{0.00113}{12}P(t)A_5(t-1) + Q_S(t)C_A(t) + Q_{45}(t)C_{45}(t) - Q_N(t)C_N(t) \tag{18}$$

where

$S_i(t)$ is the sulfate load for the ith lake box at the end of month t, in tons;

$C_{ij}(t)$ is the sulfate concentration for flow from lake box i to lake box j in month t, in tons per acre-foot; and

$C_N(t)$ is the sulfate concentration for flow from Stump Lake to Tolna Coulee.

To assign the sulfate concentrations to the flows between boxes, intermediate volumes and concentrations were calculated using equations 4 through 9 and 13 through 18, respectively, and setting all exchange flows (the Q_{ij}'s) equal to zero. The intermediate values for the ith box were denoted by $V'_i(t)$ and $S'_i(t)$. If $Q_{ij}(t)$ was positive, indicating flow from box i to box j, the sulfate concentration assigned to $Q_{ij}(t)$ was $S'_i(t)/V'_i(t)$. If $Q_{ij}(t)$ was negative, indicating flow from box j to box i, the sulfate concentration assigned to $Q_{ij}(t)$ was $S'_j(t)/V'_j(t)$.

Recorded and fitted concentrations for Devils Lake and Stump Lake for 1988-99 are shown in figure 22. The mass-balance model does not explicitly account for ice cover and associated changes in sulfate concentrations that occur during the winter. Therefore, only concentrations for open-water conditions are shown. As indicated in a later section, the proposed outlet will operate only during May-November, so accurate sulfate concentrations during ice cover are not required.

The fitted concentrations shown in figure 22 do not closely follow the recorded concentrations. Differences between the fitted and recorded concentrations, as a percentage of recorded concentrations, were particularly large for West Bay South, Main Bay, and Stump Lake, and the fitted concentrations were severely underestimated for those lake boxes for the late 1990's. The fitted concentrations for East Bay were in good agreement with the recorded concentrations for most years, but the close agreement does not necessarily indicate that sediment interaction and mixing with other boxes is not occurring in East Bay. The fitted concentrations for East Devils Lake closely followed the recorded concentrations except for 1996-99 when the fitted concentrations were overestimated.

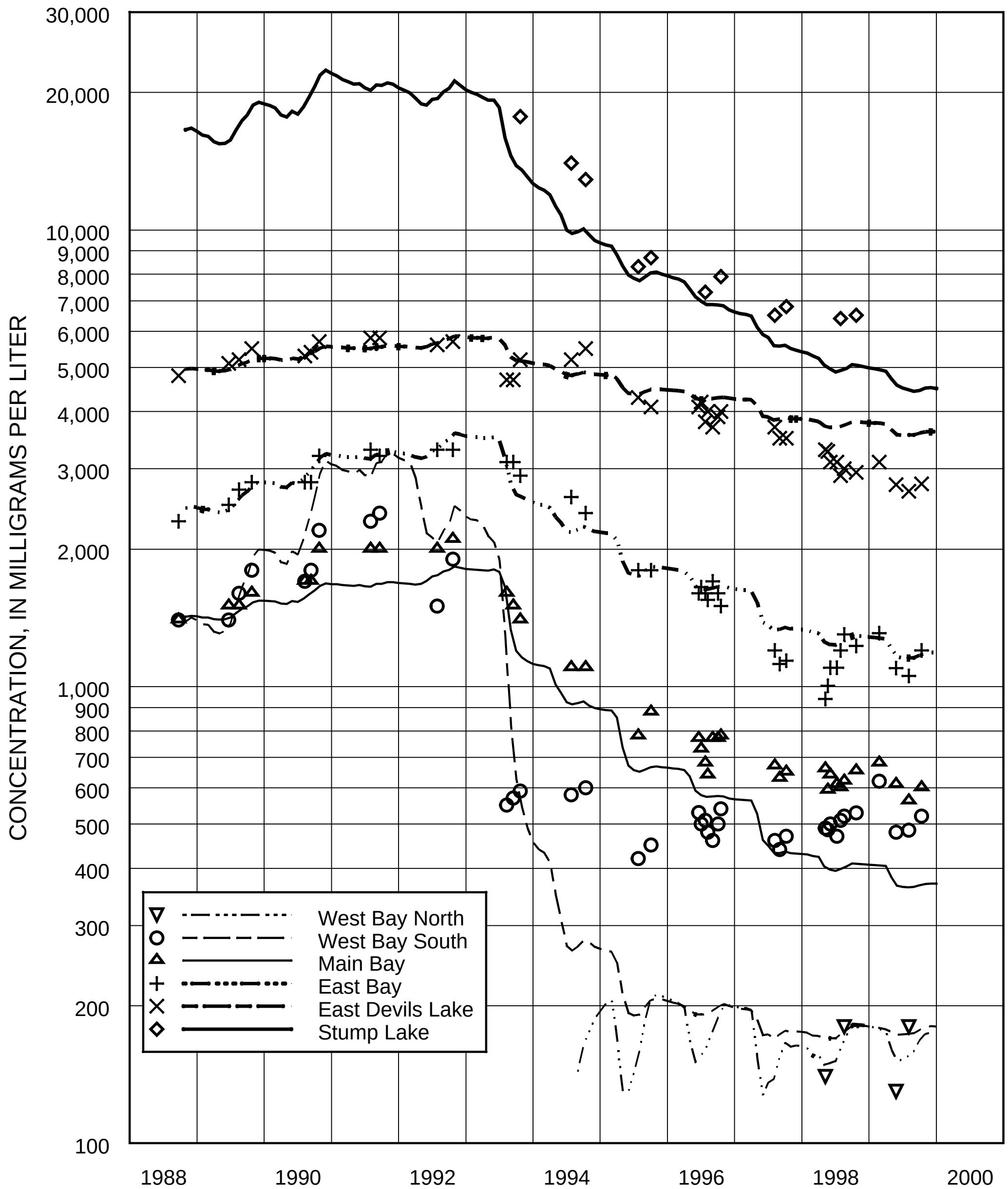

Figure 22. Recorded and fitted dissolved sulfate concentrations for Devils Lake and Stump Lake for 1988-99 from regression model with no sediment interaction and no mixing between lake boxes. (Symbols indicate recorded concentrations, and lines indicate fitted concentrations.)

Few recorded concentrations are available for West Bay North. The two concentrations shown for 1998 are for Pelican Lake, and the two concentrations shown for 1999 are for Lake Irvine. The recorded concentrations, though few, were in agreement with the fitted concentrations for box 0, indicating that sediment interaction and mixing with West Bay South probably are not significant factors in the sulfate balance for box 0 during 1988-99.

Potential causes for the lack of agreement between fitted and recorded concentrations are best explored using sulfate loads instead of sulfate concentrations. The estimated loads, which were obtained by multiplying recorded concentrations by corresponding lake-box volumes, are shown in figure 23 along with the fitted loads, which were obtained using equations 13 through 18. Total loads for lake boxes 1 through 4 also are shown in figure 23. Box 0 was not included in the total because too few water-quality data are available for that box. The solid line for total sulfate load in figure 23 indicates an increase of about 350,000 tons of sulfate in Devils Lake from 1988 to 1999 as a result of surface inflow, primarily from Big Coulee and Channel A. However, the data points indicate an actual increase of about 700,000 tons of sulfate during

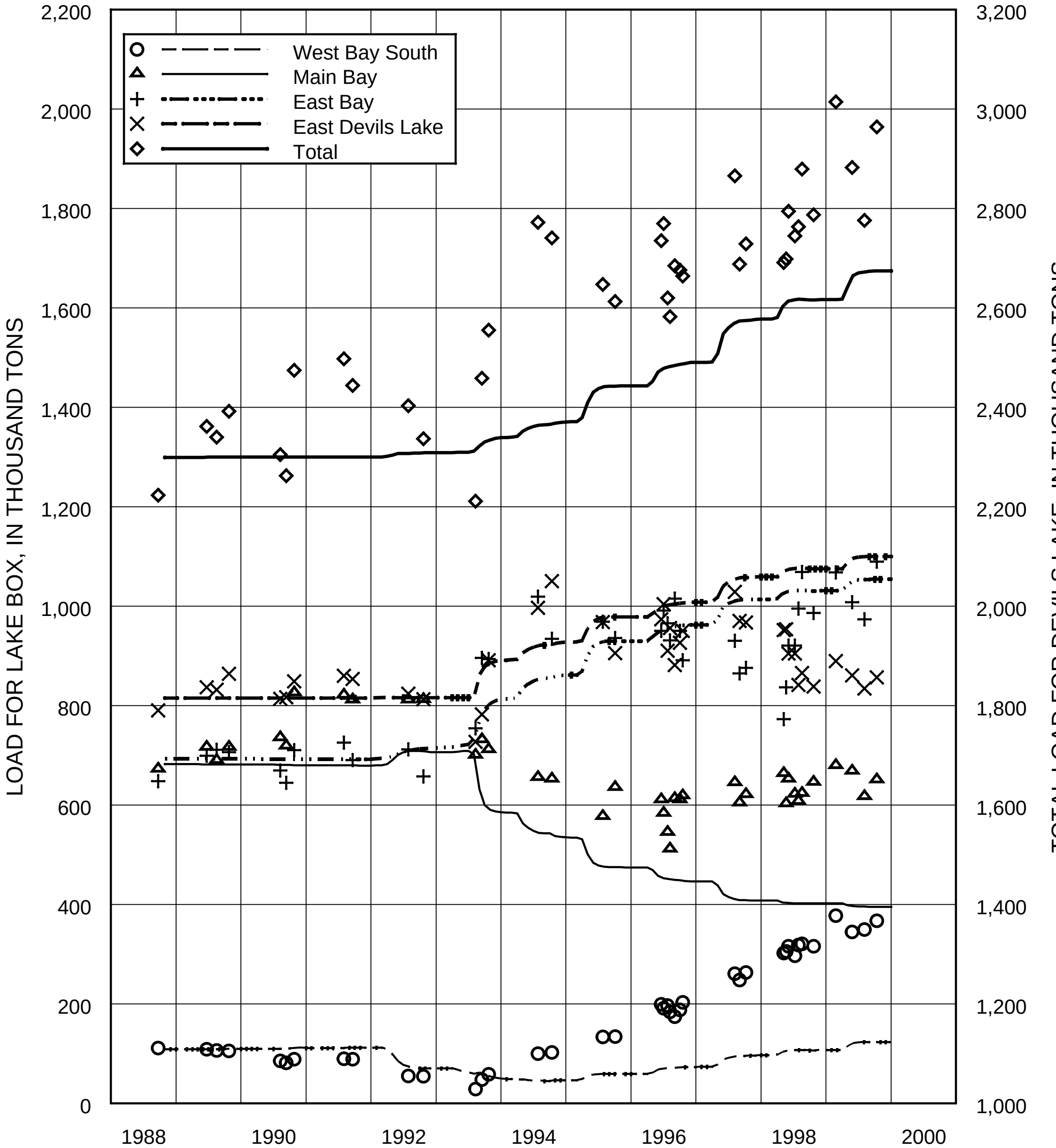

Figure 23. Estimated and fitted dissolved sulfate loads for Devils Lake for 1988-99 from regression model with no sediment interaction and no mixing between lake boxes. (Symbols indicate estimated loads, and lines indicate fitted loads.)

that period. Thus, about 350,000 tons of sulfate--much too large an amount to ascribe to errors in estimated sulfate loads for inflows--is unaccounted for. Error analysis of estimated sulfate loads for Big Coulee and Channel A indicated an error bound of less than 10 percent (about 35,000 tons) for the total estimated loads from those sources. The differences between the fitted loads and the actual loads for individual boxes are largely a result of mixing between boxes. Most of the unaccounted-for sulfate appears to be entering West Bay and Main Bay, and East Devils Lake appears to have a large sulfate deficit. However, as will be shown in a later section, most of the sulfate entering the lake from bottom sediments actually is from East Bay and East Devils Lake and is mixing back toward the west.

Sulfate Mass-Balance Model With Sediment Interaction

Lent and Lyons (1995) analyzed pore-water samples from bottom-sediment cores taken from four locations in East Bay (fig. 24) in July 1986. They described the biogeochemical processes that affect solute flux from bottom sediments for Devils Lake, including diffusional flux of major ions from highly concentrated pore water into less-concentrated lake

SEE FIGURE 24 ON NEXT PAGE.

water. They determined that diffusion of major ions from pore water into Devils Lake was occurring at each of the four locations during July 1986 and calculated estimates of the diffusion rates. In September 1996, the USGS, in cooperation with the Corps, collected and analyzed pore-water samples from bottom-sediment cores taken from seven locations in Devils Lake. The locations included three in West Bay, three in Main Bay, and one in East Bay (fig. 24). Sulfate concentrations for the July 1986 and September 1996 pore-water samples are given in table 3.

Variation of sulfate concentrations with lake location was an important consideration for this study. Therefore, each core was assigned an approximate location along a lake “centerline” from west to east. The centerline, which is described by Manous (2000), starts with zero at the Highway 19 bridge intersection with Big Coulee and extends 38.4 miles to the east end of East Devils Lake (fig. 24). Sulfate concentrations given in table 3 were related to the location along the centerline and to the depth below the lake bottom using the following regression model:

$$\log C_P = 3.113 + 0.045\ \mathrm{Min}(L_C - 18.6,\ 0) + 0.026\ \mathrm{Max}(L_C - 18.6,\ 0) + 0.074 D_B \tag{19}$$

where

C_P is the sulfate concentration for the pore water, in milligrams per liter;

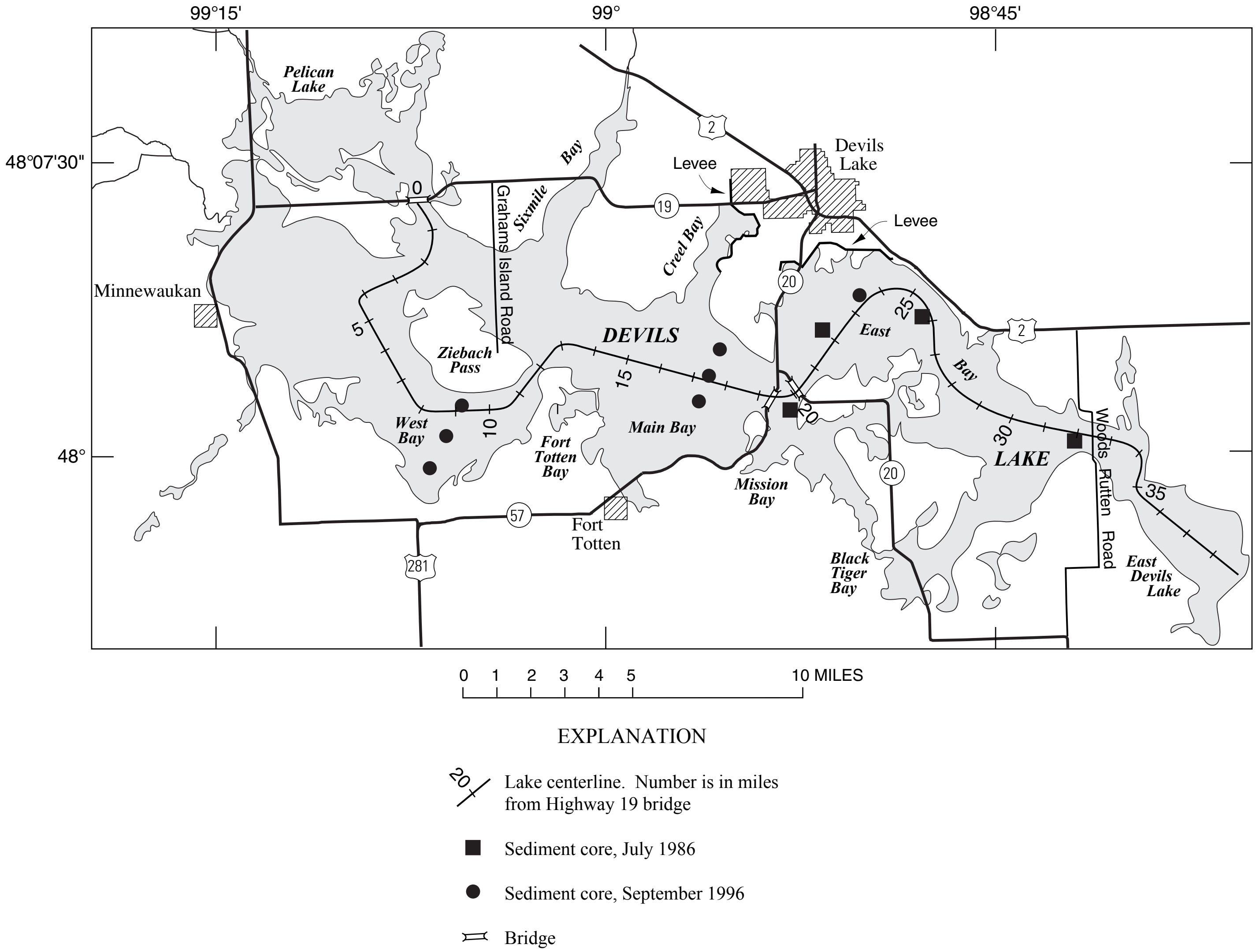

Figure 24. Locations of sediment cores taken from Devils Lake in July 1986 and September 1996.

Table 3. Sulfate concentrations for pore-water samples collected from Devils Lake in July 1986 and September 1996

Core number[1]	Date	Centerline location[2] (miles)	Sulfate concentration for lake water (milligrams per liter)[3]	Depth below lake bottom (inches); sulfate concentration (milligrams per liter)		
1	July 1986	19.8	--	(1.18; 2,100) (4.92; 2,540)	(1.77; 2,100) (6.89; 4,200)	(3.15; 2,480)
2	July 1986	21.7	--	(1.18; 1,900) (4.72; 3,390)	(1.77; 2,100) (6.30; 3,690)	(3.15; 2,650) (7.87; 4,430)
3	July 1986	25.4	--	(1.18; 2,220) (4.92; 5,000)	(1.77; 2,260) (6.89; 7,200)	(3.15; 3,280) (8.86; 9,130)
4	July 1986	31.6	--	(1.18; 3,800) (5.12; 6,400)	(1.97; 4,560)	(3.54; 9,500)
5	September 1996	9.3	506	(1.18; 627)	(1.97; 691)	
6	September 1996	9.3	355	(1.18; 522) (3.54; 639)	(1.97; 557) (4.33; 928)	(2.76; 598) (5.12; 1,400)
7	September 1996	9.3	424	(1.18; 613) (3.54; 1,090)	(1.97; 687) (4.33; 1,280)	(2.76; 852)
8	September 1996	17.4	671	(1.18; 1,660) (3.54; 2,190)	(1.97; 1,620) (4.33; 2,370)	(2.76; 2,060) (5.12; 2,440)
9	September 1996	17.4	646	(1.18; 1,030) (3.54; 1,900)	(1.97; 1,390) (4.33; 2,260)	(2.76; 1,670)
10	September 1996	17.4	678	(1.18; 1,040) (3.54; 1,610)	(1.97; 1,270) (4.33; 1,670)	(2.76; 1,430)
11	September 1996	22.9	1,470	(1.18; 1,820) (3.54; 2,510)	(1.97; 1,880)	(2.76; 2,080)

[1]Cores 1 through 4 from Lent and Lyons (1995); cores 5 through 11 from U.S. Geological Survey (data on file at Bismarck, N. Dak., office).

[2]Approximate location along lake centerline defined by Manous (2000).

[3]Depth-averaged concentration at location of pore-water samples.

$\mathrm{Min}(L_C - 18.6, 0)$ is the minimum of $L_C - 18.6$ and 0;

L_C is the location of the core along the lake centerline, in miles;

$\mathrm{Max}(L_C - 18.6, 0)$ is the maximum of $L_C - 18.6$ and 0; and

D_B is the depth below the lake bottom, in inches.

The regression model explained much of the variation in the log-transformed sulfate concentrations. The coefficient of determination was 95 percent, and all coefficients were highly significant (p-values less than 0.01). The two terms given in the model to relate the concentrations to the location along the centerline were necessary because of a break in slope at about 18.6 miles, which is just west of the Highway 57 bridge between Main Bay and Mission Bay (Mission Bay was included with East Bay in the mass-balance model). Results from the model indicate a 0.045 decrease in the base-10 logarithm of concentration for each mile of distance west of the break and a 0.026 increase for each mile of distance east of the break. The relation between lateral distance from the centerline and sulfate concentration was not significant. However, results from the model do indicate a highly significant increase in concentration with depth below the lake bottom--a 0.074 increase in the base-10 logarithm of concentration occurred for each inch of depth. Graphical analysis of the residuals of the concentrations indicated no obvious differences in the relation between concentration and depth for the different sampling locations and no deviations from a log-linear relation, but the mean of the residuals for the 1986 data was slightly higher than the mean for the 1996 data. Thus, the concentrations in the shallow bottom sediments may have decreased slightly during 1986-96, indicating a slow depletion of sulfate in the bottom sediments. However, the difference was not statistically significant and was too small to account for the large flux of sulfate into Devils Lake during that time. Therefore, sulfate entering the lake from the shallow sediments evidently was being replaced by sulfate from the deep sediments.

To determine the flux of sulfate between the bottom sediments and Devils Lake, the regression model (eq. 19) was used as the starting point to develop a conceptual model of sulfate diffusion between pore water and lake water. A sediment “box” of cross-section area A_S and depth D_S was centered on a particular location along the lake centerline. The shape of the box was not important because only the area of contact between the top of the box and the lake was required for the diffusion model. The pore water in the box was assumed to have a constant sulfate concentration expressed, in accordance with equation 19, as

$$\log C_P = a_0 + 0.045\ \mathrm{Min}(L_C - 18.6,\ 0) + 0.026\ \mathrm{Max}(L_C - 18.6,\ 0) \tag{20}$$

where

a_0 is an estimated coefficient.

The constant concentration assigned to the pore water in the box was an approximation because the actual concentration increased continuously with depth as indicated in equation 19. The concentration depended on the value of a_0 and was an “effective concentration” that was between the concentration at the top of the box and the concentration at the bottom of the box. a_0 was expected to increase as the depth of the box increased, but the actual relation between a_0 and the depth of the box was not required.

Because diffusion of sulfate can occur between bottom sediments and the lake and between shallow sediments and deep sediments, a series of three sediment boxes was used to determine the flux of sulfate into Devils Lake. The boxes were stacked one on top of another, had the same cross-section area, A_S, and were located at the same location along the lake centerline (three boxes were determined through trial and error to be sufficient to model the long-term sulfate fluxes). The thicknesses of the boxes were defined as

$$D_S(1) = 0.65 \text{ foot; } D_S(2) = 0.65 \text{ foot; and } D_S(3) = 5.25 \text{ feet} \tag{21}$$

where

$D_S(k)$ is the thickness of the kth sediment box below the sediment-lake interface, in feet.

The two sediment boxes closest to the sediment-lake interface were assumed to have thicknesses of 0.65 foot and were used to model the flux of sulfate from deep sediments, through shallow sediments, into the lake. The deepest box was assumed to have a thickness of 5.25 feet and was used as a reservoir to supply sulfate from deep sediments to the lake.

The porosities (the volume of water divided by the volume of core sample, in percent) for the September 1996 bottom-sediment cores were used to determine the volume of pore water in each of the sediment boxes. The porosities decreased with distance from the lake bottom and, for Main Bay, ranged from about 89 percent near the sediment-lake interface to about 76 percent 4 inches below the interface. For West Bay, the porosities ranged from about 81 percent near the sediment-lake interface to about 60 percent 4 inches below the interface. For East Bay, the porosities ranged from about 85 percent near the sediment-lake interface to about 74 percent 4 inches below the interface. Based on these data, a porosity of 80 percent was assigned to the box immediately below the lake bottom. Porosities in successive boxes were assumed to decrease as follows:

$$P(1) = 0.8;\ P(2) = 0.4;\ \text{and } P(3) = 0.2 \tag{22}$$

where

$P(k)$ is the porosity (the volume of water divided by the volume of the sediment box) for the kth sediment box below the sediment-lake interface.

The volume of water in the kth sediment box was, thus, given by

$$V_P(k) = A_S D_S(k) P(k) \qquad (23)$$

where

$V_P(k)$ is the volume of pore water in the kth sediment box, in acre-feet; and

A_S is the cross-section area of the sediment boxes, in acres.

Given the volume of water and the sulfate concentration for the pore water in each sediment box, the sulfate load for the kth box could be determined using the following equation:

$$L_P(k) = V_P(k) C_P(k) \qquad (24)$$

where

$L_P(k)$ is the sulfate load for the kth sediment box, in tons; and

$C_P(k)$ is the sulfate concentration for the pore water in the kth sediment box, in tons per acre-foot.

The flux of sulfate between the sediment box adjacent to the lake bottom and the lake itself was approximated for a small time increment (which for this analysis was 1 day) using the following equation (Callender and Hammond, 1982; Lent and Lyons, 1995):

$$F_{1L} = fP(1) A_S [C_P(1) - C_L] \qquad (25)$$

where

F_{1L} is the flux of sulfate from sediment box 1 to the lake in 1 day, in tons;

f is a positive estimated flux coefficient;

$C_P(1)$ is the sulfate concentration for the pore water in sediment box 1 at the start of the day, in tons per acre-foot; and

C_L is the sulfate concentration for the lake at the start of the day, in tons per acre-foot.

Similarly, the flux of sulfate between successive sediment boxes on a particular day was approximated by

$$F_{k+1,k} = fP(k+1) A_S [C_P(k+1) - C_P(k)] \text{ for } k = 1 \text{ or } 2 \qquad (26)$$

where

$F_{k+1,k}$ is the flux of sulfate from sediment box $k+1$ to sediment box k in 1 day, in tons.

Only positive fluxes (that is, toward the lake) were allowed, so the flux was set equal to zero if the corresponding concentration difference was negative.

Because a single series of sediment boxes was not adequate to account for the west-to-east increase in sulfate concentrations in the bottom sediments of Devils Lake, boxes were included in the sulfate mass-balance model for 13 locations along the lake centerline from west to east and for one location on Stump Lake. The locations along the centerline were in West Bay South (at 9.3 and 10.5 miles), Main Bay (at 13.6, 14.9, 16.1, 17.4, and 18.5 miles), East Bay (at 19.8, 22.3, 24.8, 28.5, and 30.4 miles), and East Devils Lake (at 36.0 miles). The locations were selected so that each represented approximately the same area of contact between deep sediments and the lake. The lakebed in West Bay South at locations less than 9.3 miles along the centerline consisted of recently inundated areas and was not expected to contribute significantly to the flux of sulfate from the bottom sediments. Similarly, the lakebed in West Bay North also was not expected to contribute significantly to the flux of sulfate. For each of the 14 locations, a series of three boxes, as described previously, was included in the model. Thus, the model included a total of 42 boxes.

To adjust the monthly sulfate mass-balance equations (eqs. 13 through 18) to account for sediment interaction, the sulfate concentrations for the first layer of boxes on September 30, 1988, were assumed to be given by equation 20. The locations along the lake centerline were as defined in the previous paragraph. September 30, 1988, was chosen as the starting date for the sulfate mass-balance computation because in-lake sulfate concentrations were readily available beginning on that date. Starting concentrations for the second and third layers of boxes also were required for the model so equation 19 was used to extrapolate concentrations for the shallow sediments to the deep sediments. To use equation 19, the starting concentrations for the second layer of boxes (which was 7.9 inches deeper than the first layer of boxes) needed to be 3.8 ($10^{0.58}$) times higher than the concentrations for the first layer of boxes. However, because those concentrations were too high to match historical fluxes of sulfate into the lake, the starting concentrations for the second layer of boxes were selected by trial and error to be equal to two times the starting concentrations for the first layer of boxes. Similarly, the starting concentrations for the third layer of boxes were set equal to two times the starting concentrations for the second layer of boxes. Those concentrations provided good matches for the historical flux rates as indicated in the following discussion.

The unknown parameters [a_0 (eq. 20), f (eq. 25), and A_S (eq. 25)] were estimated using a nonlinear regression model to minimize the sum-of-squared errors between recorded and computed in-lake sulfate concentrations for 1988-99. The computed sulfate concentrations were obtained by letting $S_i(t)$ denote the sulfate load for the ith lake box at the end of month t and assuming no sediment interaction (eqs. 13 through 18 with $t = 1$ corresponding to October 1988). The sulfate loads for the sediment layers at the beginning of the month were given by

$$L_P(k, j) = V_P(k) C_P(k, j) \tag{27}$$

where

$L_P(k, j)$ is the sulfate load for the kth sediment layer at location j at the beginning of the month, in tons (eq. 24 with j denoting the location along the lake centerline); and

$C_P(k, j)$ is the sulfate concentration for the kth sediment layer at location j at the beginning of the month, in tons per acre-foot.

The sulfate load for the ith lake box at the end of the month then was adjusted for the daily fluxes of sulfate for the month using the following equation:

$$S'_i(t) = S_i(t) + \Sigma_d \Sigma_{j/i} F_{1L}(j) \tag{28}$$

where

$S'_i(t)$ is the sulfate load for the ith lake box at the end of month t adjusted for sediment interaction, in tons;

Σ_d denotes the sum over all days in month t;

$\Sigma_{j/\mathrm{i}}$ denotes the sum over all locations j within lake box i; and

$F_{1L}(j)$ is the flux of sulfate from bottom sediments into the lake at location j in 1 day, in tons (eq. 25).

Sulfate loads for the sediment boxes also were adjusted at the end of each month to account for the daily fluxes between the top sediment layer and the lake and between the deeper sediment layers using the following equation:

$$L'_P(k, j) = L_P(k, j) + \Sigma_d[F_{k+1, k}(j) - F_{k, k-1}(j)], k = 1, 2, \text{ or } 3 \tag{29}$$

where

$L'_P(k, j)$ is the sulfate load for the kth sediment layer at location j at the end of the month, in tons;

$F_{k+1, k}(j)$ is the flux of sulfate from sediment layer $k + 1$ to sediment layer k at location j, in tons;

$F_{4, 3}(j)$ equals zero; and

$F_{1, 0}(j)$ equals $F_{1L}(j)$ (eq. 28).

For each daily time step, the sulfate loads and associated concentrations from the previous day were updated to account for the daily fluxes as they occurred. Each lake box and each sediment box was assumed to be completely mixed at the end of each day, and the volume of water in each lake box was held fixed at the value obtained using equations 4 through 9.

The parameters (a_0, f, and A_S) that control the flux of sulfate from bottom sediments needed to be estimated in tandem with the parameters, described in a later section, that control mixing between the lake boxes because in-lake sulfate concentrations affect the flux rates as indicated by equation 25. Therefore, the parameter estimates and the associated model output will be described in detail after the correction for mixing between lake boxes is described.

Sulfate Mass-Balance Model With Mixing Between Lake Boxes

The degree of mixing between lake boxes is controlled largely by the geometry of the connections between the lake boxes. Properties of these connections for Devils Lake are given in table 4. Several changes in the connections occurred during the sulfate mass-balance computation period (1988-99). For example, in the sulfate mass-balance computations for before 1997, the Highway 57 bridge opening was used as the connection between Main Bay and East Bay. During the heavy flooding of 1997, Highways 20 and 57 were submerged and the cross-section area between Main Bay and East Bay was not known. In 1998, Highway 20 was raised and the bridge was replaced, but Highway 57 was still under water. Therefore, in the sulfate mass-balance computations for 1998 and 1999, the Highway 20 bridge opening was used as the connection between Main Bay and East Bay. In 1999, Highway 57 was raised and a new bridge was completed. Therefore, in the simulations of future lake levels, the new Highway 57 bridge opening was used as the connection between Main Bay and East Bay. Also, before 1998, East Bay and East Devils Lake were connected by two 6-foot culverts under Woods Rutten Road that had a bottom elevation of 1,425 feet above sea level. In 1998, Woods Rutten Road was submerged and the cross-section area between East Bay and East Devils Lake was not known. Woods Rutten Road was raised in the fall of 1998, and the original culverts were replaced by four 6-foot culverts that had a bottom elevation of 1,434 feet above sea level.

Table 4. Properties of connections between lake boxes

[<, less than; >, greater than]

Connection	Effective date	Lake level (feet above sea level)	Approximate cross-section area (square feet)	Equation for approximate cross-section area[1]
West Bay-Main Bay (Ziebach Pass)	1988 to present	1,421	0	$A = 240H,\ 0 < H < 5;$
		1,426	1,200	$A = 1,200 + 1,200(H - 5),$
		1,432	8,400	$5 < H < 11;$
		1,440	21,200	$A = 8,400 + 1,600(H - 11),\ H > 11$
		1,450	37,200	
Main Bay-Mission Bay (Highway 57 bridge)	1988-97[2]	1,420	0	$A = 71H + 2H^2,\ 0 < H < 20$
		1,426	498	
		1,432	1,140	
		1,440	2,220	
Main Bay-Mission Bay (Highway 57 bridge)	1999 to present[3]	1,415	0	$A = 28H + 2H^2,\ 0 < H < 43$
		1,426	550	
		1,432	1,054	
		1,440	1,950	
		1,450	3,430	
Mission Bay-East Bay (Highway 20 bridge)	1988-97[4]	1,415	0	$A = 36H + 2H^2,\ 0 < H < 25$
		1,426	638	
		1,432	1,190	
		1,440	2,150	
Mission Bay-East Bay (Highway 20 bridge)	1998 to present[5]	1,421.5	0	$A = 36H + 2H^2,\ 0 < H < 27$
		1,426	202	
		1,432	598	
		1,440	1,350	
		1,450	2,430	
East Bay-East Devils Lake	1988-98[6]	1,425	0	$A = 57H/6,\ 0 < H < 6$
		1,431	57	
East Bay-East Devils Lake	1999 to present[7]	1,434	0	$A = 114H/6,\ 0 < H < 6$
		1,440	114	

[1] A is the cross-section area, in square feet, and H is the height of the water surface above the bottom of the cross section, in feet.

[2] Elevation of bridge deck is 1,440 feet above sea level. Roadway was submerged in 1997.

[3] Elevation of bridge deck is 1,458 feet above sea level. New roadway and bridge were completed in 1999.

[4] Elevation of bridge deck is 1,440 feet above sea level. Roadway was submerged in 1997.

[5] Elevation of bridge deck is 1,448.5 feet above sea level. New roadway and bridge were completed in 1998.

[6] Two 6-foot culverts under Woods Rutten Road. Roadway was submerged in 1998.

[7] Four 6-foot culverts under Woods Rutten Road. New roadway was completed in fall of 1998.

The connection between West Bay and Main Bay (Ziebach Pass) is a natural feature and has not been changed. Although the bottom elevation of the connection is actually 1,417 feet above sea level, the mass-balance computations provided a better representation of mixing between West Bay and Main Bay by assuming a bottom elevation of 1,421 feet above sea level or, in effect, assuming no mixing occurs below a level of 1,421 feet above sea level. At lake levels between 1,421 and 1,426 feet above sea level, the cross-section area between West Bay and Main Bay increases about 240 square feet per foot of rise, and at lake levels greater than about 1,426 feet above sea level, the cross-section area increases much more rapidly. Ziebach Pass has by far the largest cross-section area of any of the connections at lake levels greater than 1,426 feet above sea level.

The connection between Devils Lake and Stump Lake consists of a long, narrow channel that has a bottom elevation of 1,446.5 feet above sea level at the upstream control location. Even if Devils Lake “joins” with Stump Lake and continues to rise to the natural spill elevation to the Sheyenne River (1,459 feet above sea level), the channel that connects East Devils Lake and Stump Lake still will consist of a narrow channel, about 4 miles long, that would greatly hinder mixing between the two lake boxes. Therefore, the assumption that no mixing occurs between East Devils Lake and Stump Lake was used for further development of the outlet simulation model. However, movement of sulfate due to gravity flow can occur between East Devils Lake and Stump Lake. Although flow usually is from East Devils Lake to Stump Lake, flow can occur in the reverse direction in the outlet simulation model when pumping from the west end of Devils Lake causes lake levels to decline and induces gravity flow of water from east to west.

During periods of open water and relatively stable lake levels (that is, when the hydraulic gradient from west to east is small), exchange flows between lake boxes are predominately from wind-induced head differences between the boxes. Flow tends to be nonstratified (that is, entirely in one direction or the other) and the flow rates are not substantially affected by density differences between water in the boxes (Manous, 2000). In such conditions, the volume of water exchanged between boxes during a given time step can be estimated from the cross-section area of the connection between the boxes and the cross-section average flow velocity. The cross-section average flow velocity depends on the still-water (that is, with no wind) lake level and the wind-induced head difference between boxes.

The cross-section average flow velocity for each connection was estimated using a hydrodynamic flow and sulfate-transport model for Devils Lake developed by Manous (2000). The model was calibrated using detailed flow, water-quality, and meteorological data collected during the summer of 1998 at several locations in Devils Lake. These locations included the connections between lake boxes as defined previously. Results from model runs for various still-water lake levels are given in table 5. For a stable lake level of 1,450 feet above sea level during a “typical” open-water season (as

Table 5. Estimated average flow velocities based on wind-induced head differences for connections between lake boxes

[Data from Joe Manous, U.S. Military Academy at West Point, written commun., 2001; average daily flows are based on weather conditions from April 27, 1998, to November 24, 1998]

Lake level (feet above sea level)	Connection							
	West Bay-Main Bay (Ziebach Pass)		Main Bay-Mission Bay (Highway 57)		Mission Bay-East Bay (Highway 20)		East Bay-East Devils Lake (Woods Rutten Road)	
	Average daily flow (cubic feet per second)	Flow velocity[1] (feet per second)	Average daily flow (cubic feet per second)	Flow velocity[1] (feet per second)	Average daily flow (cubic feet per second)	Flow velocity[1] (feet per second)	Average daily flow (cubic feet per second)	Flow velocity[1] (feet per second)
1,434	1,516	0.131	748	0.95	696	0.91	0	0
1,436	1,600	.108	865	.90	811	.86	18	.47
1,438	1,665	.092	972	.84	917	.81	65	.86
1,440	1,721	.081	1,074	.79	1,020	.76	110	.96
1,442	1,772	.073	1,171	.74	1,116	.71	133	1.17
1,444	1,790	.065	1,197	.71	1,136	.68	133	1.17
1,446	1,804	.059	1,218	.68	1,153	.65	133	1.17
1,448	1,816	.053	1,235	.66	1,168	.62	134	1.18
1,450	1,826	.049	1,249	.63	1,179	.60	134	1.18
1,452	1,834	.045	1,262	.61	1,189	.57	134	1.18
1,454	1,841	.042	1,272	.58	1,197	.55	134	1.18

[1]Average daily flow, in cubic feet per second, divided by approximate cross-section area, in square feet.

represented by weather conditions in 1998), the average daily flow from Main Bay to West Bay is 1,826 cubic feet per second [the average daily flow in the reverse direction (West Bay to Main Bay) also is 1,826 cubic feet per second because the lake levels remain constant]. These flows correspond to a total exchange-flow volume for a typical 210-day open-water season of about 763,000 acre-feet. However, because inflows cause rising lake levels and hydraulic gradients from west to east during certain times of the year, the actual exchange-flow volume could be less than 763,000 acre-feet. Density differences between the water in Main Bay and the water in West Bay (because of differences in dissolved ion concentrations or temperature) also tend to hinder mixing. In the extreme case, flow from Main Bay to West Bay during a particular wind event could become a “wedge” of water that flows back into Main Bay, without mixing with West Bay water, when the wind subsides or reverses direction. In such a case, no sulfate would be exchanged between Main Bay and West Bay because the amount of sulfate exchanged as a result of exchange flow depends on the efficiency of the mixing.

The exchange-flow volumes calculated using the hydrodynamic model provided only an approximate estimate of the actual exchange-flow volumes. However, the calculated volumes were used to develop an equation to relate flow velocities and lake level for each of the connections. The general equation used for this purpose is

$$V_E = \frac{Q_E}{(1.98A)} = aH^b \tag{30}$$

where

V_E is the cross-section average daily flow velocity, in feet per second;

Q_E is the exchange flow, in acre-feet per day;

A is the cross-section area, in square feet;

H is the height of the water surface above the bottom of the cross section, in feet; and

a and b are constants.

Values of a and b were selected for each cross section to fit the data points shown in figure 25 and given in table 5. The values obtained for a and b were a = 2.28 and b = -1.15 for Ziebach Pass, a = 3.5 and b = -0.5 for Highway 57, a = 3.2 and b = -0.5 for Highway 20, and a = 0.39 and b = 0.5 for Woods Rutten Road. As shown in figure 25, the fitted curves provided a close approximation to the data. The flow velocity for the connection between East Bay and East Devils Lake (culverts under Woods Rutten Road) increased as lake levels rose above the bottom elevation (1,434 feet above sea level) and remained constant at lake levels greater than 1,443 feet above sea level (fig. 25). The velocities for the other connections decreased as lake levels increased. The velocities for the two bridge openings under Highways 20 and 57 were similar, and the velocities for Ziebach Pass were much lower than the velocities for the bridge openings.

Although equation 30 is difficult to interpret hydraulically, the exponent for both bridge openings was b = -0.5. Velocity in an open channel that connects two reservoirs is approximately proportional to the square root of the head difference between the upstream and downstream locations (Matthai, 1968), and wind-induced head differences are approximately proportional to the inverse of lake depth (Manous, 2000). Therefore, velocities approximately proportional to $H^{-0.5}$ are consistent with hydraulic theory.

During periods of ice cover, exchange flows between lake boxes are predominately from high-density water to low-density water. Because water density increases as the dissolved ion concentration increases, after formation of ice cover, water begins to flow from the lake box that has the higher concentration to the lake box that has the lower concentration. The flow of dense water toward less-dense water causes the water level of the receiving lake box to increase until the level becomes high enough to cause stratified flow in both directions. Eventually, an equilibrium point is reached when flow in both directions is the same, and a layer of dense water flows one direction below a layer of less-dense water that flows the opposite direction. The approximate equilibrium exchange flow is given by the following equation (Wilkinson, 1986):

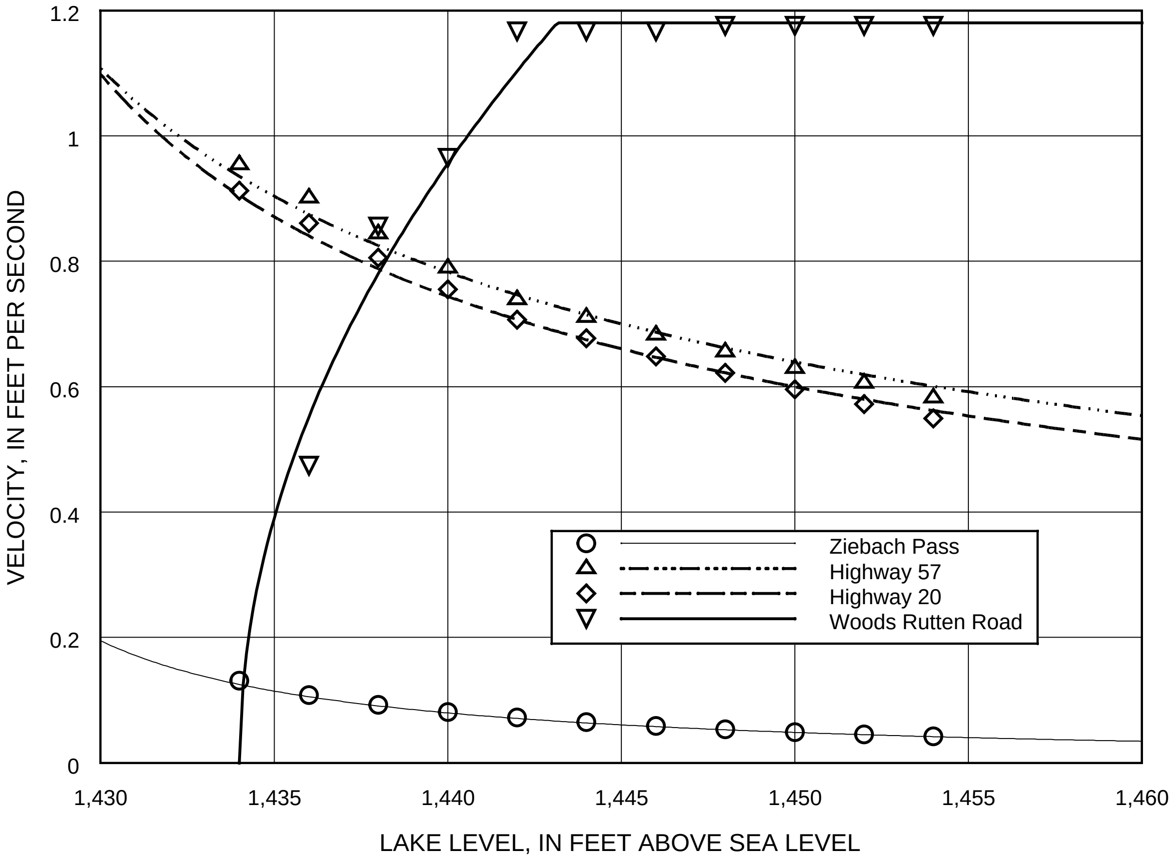

Figure 25. Average flow velocity based on wind-induced head differences for connections between lake boxes. (Symbols indicate values from hydrodynamic model, and lines indicate fitted values.)

$$Q_{EI} = 11.21\left[\frac{(\rho_1 - \rho_2)}{\rho}\right]^{\frac{1}{2}} A_I^{\frac{5}{4}} \tag{31}$$

where

Q_{EI} is the equilibrium exchange flow under ice, in acre-feet per day;

ρ_1 is the density of the high-density water;

ρ_2 is the density of the low-density water;

ρ is the average density of the two reservoirs; and

A_I is the cross-section area of the connection under ice, in square feet.

For typical (less than 10,000 milligrams per liter) dissolved ion concentrations in Devils Lake and assuming the dissolved ion concentration is directly proportional to the sulfate concentration, equation 31 is approximately equivalent to

$$Q_{EI} = 0.106(C_1 - C_2)^{\frac{1}{2}} A_I^{\frac{5}{4}} \tag{32}$$

where

C_1 is the sulfate concentration for the high-density water, in tons per acre-foot; and

C_2 is the sulfate concentration for the low-density water, in tons per acre-foot.

Given the open-water mixing equation (eq. 30), the ice-covered mixing equation (eq. 32), and the equation to compute sulfate loads adjusted for sediment interaction (eq. 28), the sulfate load for the ith box at the end of a particular month, adjusted for sediment interaction and mixing between boxes, was computed using the following equation:

$$S''_i(t) = S_i(t) + \Sigma_d\{\Sigma_{j/i}F_{1L}(j) + m_i Q_{Ei}(C_{i+1} - C_i)\} \tag{33}$$

where

$S''_i(t)$ is the sulfate load for the ith lake box at the end of month t adjusted for sediment interaction and mixing between lake boxes, in tons;

m_i is a mixing coefficient for exchange flow between lake box i and lake box $i + 1$;

Q_{Ei} is the exchange flow between lake box i and lake box $i + 1$, in acre-feet, computed from either equation 30 or 32; and

C_i is the sulfate concentration for the ith lake box, in tons per acre-feet.

For each daily time step, the sulfate loads and associated concentrations from the previous day were updated to account for the daily fluxes as they occurred. Each lake box was completely mixed at the end of each day, and the volume of water in each box was held fixed at the value obtained using equations 4 through 9. The mixing coefficients were necessary because, as indicated previously, the actual amount of sulfate exchanged between the boxes depends on the efficiency of the mixing. Thus, the "effective" exchange flow $(m_i Q_{Ei})$ was expected to be less than the exchange flow computed from either equation 30 or 32. The open-water mixing equation (eq. 30) was used for April through November, and the ice-covered mixing equation (eq. 32) was used for December through March. When using equation 32, the cross-section area was reduced to account for an assumed 3.5 feet of ice cover each winter.

The unknown parameters that control the sulfate mass balance were estimated using nonlinear least-squares regression to minimize the sum-of-squared errors between the base-10 logarithms of recorded and computed sulfate concentrations for 1988-99. As indicated previously, those parameters include a parameter that controls the starting sulfate concentration for the pore water in the sediment (a_0 in eq. 20), a parameter that controls the flux of sulfate between the pore water and the lake (f in eq. 25), a parameter that controls the effective area of contact between the bottom sediments and the lake (A_S in eq. 23), and parameters that control the mixing between lake boxes (the m_i's in eq. 33). Log-transformed concentrations were used because the variability of the regression residuals for log-transformed values was much more uniform among the lake boxes and through time than the variability of the residuals for untransformed values.

The parameter estimates for the nonlinear regression model did not converge when all of the parameters were allowed to vary independently. The nonconvergence was caused by a strong negative correlation between the estimates for a_0 and A_S. Therefore, because an increase in the starting sulfate concentration of the pore water (an increase in a_0) can be offset by a decrease in the area of contact (a decrease in A_S), resulting in similar sulfate concentrations, A_S was held fixed at 1,600 acres for each sediment box. The remaining parameters were estimated using nonlinear least-squares regression. Although the total area of contact could not be determined exactly, a value of 22,400 acres (1,600 acres times 14 sediment boxes) was considered reasonable. In addition to fixing A_S, m_0 (the mixing coefficient for exchange flow between West Bay North and West Bay South) and m_4 (the mixing coefficient for exchange flow between East Devils Lake and Stump Lake) were held fixed at zero. As indicated previously, significant mixing has not occurred historically at those connections and mixing is assumed to be negligible in the future. Potential overtopping of Highway 19, which would affect mixing between West Bay North and West Bay South, will be considered in a later section.

Parameter estimates obtained from the nonlinear regression model are given in table 6, and the fitted sulfate concentrations are shown in figure 26. The parameter estimates are within reasonable limits of the expected actual parameter values, and the fitted sulfate concentrations closely follow the recorded sulfate concentrations. The estimated value of a_0 (3.62) is within the range expected for the pore-water samples collected during 1986 and 1996. The potential values from equation 19 ranged from 3.113 (at the sediment-lake interface) to 3.69 (7.87 inches below the interface). The starting in-lake sulfate concentration for Stump Lake was not known, so the starting sulfate concentration for that lake box was selected by trial and error to be 15,000 milligrams per liter. The starting concentration for the sediment box closest to the sediment-lake interface with Stump Lake, also selected through trial and error, was 36,000 milligrams per liter. The estimated value for f was not directly comparable to estimated values from previous studies, such as Lent and Lyons (1995), because flux coefficients computed in previous studies were laboratory-derived coefficients that depended on the specific times and locations of the cores. The flux coefficient computed for this study is an effective coefficient for the entire lake and remains constant through time. The estimated values for m_1, m_2, and m_3 are all less than 1, as expected, and indicate that perfect mixing was not occurring at the connections between the lake boxes. The most efficient mixing (as indicated by the largest coefficient) occurred between East Bay and East Devils Lake, where flow is controlled by submerged culverts that have a small cross-section area. The least efficient mixing occurred between Main Bay and East Bay, partly because the model assumes flow occurs directly between the two bays when, in fact, Mission Bay separates Main Bay from East Bay. The mixing coefficient between West Bay and Main Bay is relatively small, indicating that mixing is not very efficient between those bays. However, because of the large cross-section area of that connection, large amounts of sulfate still are being exchanged.

Table 6. Parameter estimates obtained from nonlinear regression model used to compute in-lake sulfate concentrations

Parameter	Primary role of parameter	Parameter estimate	Approximate 95-percent confidence interval
a_0	Determines initial sulfate concentration of pore water in bottom sediments	3.62	3.55 to 3.69
f	Controls flux of sulfate between pore water and lake	.0011	0.0008 to 0.0014
m_1	Controls mixing between West Bay and Main Bay (Ziebach Pass)	.23	0.16 to 0.30
m_2	Controls mixing between Main Bay and East Bay (Highways 57 and 20)	.18	0.14 to 0.22
m_3	Controls mixing between East Bay and East Devils Lake	.55	0.41 to 0.69

Detailed sulfate mass-balance data for 1988-99 are shown in figures 27 through 29. As shown in figure 27, estimated sulfate loads for Devils Lake for 1988-99 closely agree with fitted sulfate loads. The correction for sediment interaction resulted in a much better agreement between the total loads than that obtained from the model with no sediment interaction (fig. 23), and the correction for mixing between lake boxes resulted in a much better distribution of sulfate loads among the lake boxes. As shown in figure 28, the largest contribution of sulfate from bottom sediments occurred in Stump Lake although the area of contact for Stump Lake is much smaller than the area for Main Bay and East Bay. The next highest contribution occurred in East Bay and was followed by contributions in Main Bay, East Devils Lake, and West Bay South. In all lake boxes, contributions declined during 1988-92 when lake levels were decreasing and in-lake sulfate concentrations were increasing. Contributions increased rapidly in 1993 during the rapid rise and resulting freshening of the lake and then generally declined from 1994 to 1999 although in-lake sulfate concentrations also continued to decline during that period. Evidently, sulfate in the bottom sediments was being depleted during 1994-99, and pore-water concentration gradients were being reduced.

The estimated fluxes of sulfate between lake boxes (fig. 29) are estimates of the total amount of sulfate exchanged between the boxes and include contributions from gravity flow of water (eqs. 13 to 18) and contributions from mixing as a result of exchange flows (eq. 33). The fluxes are positive when gravity flow of water from west to east is sufficient to overcome mixing (usually during spring runoff) and negative when gravity flow of water is small and mixing causes

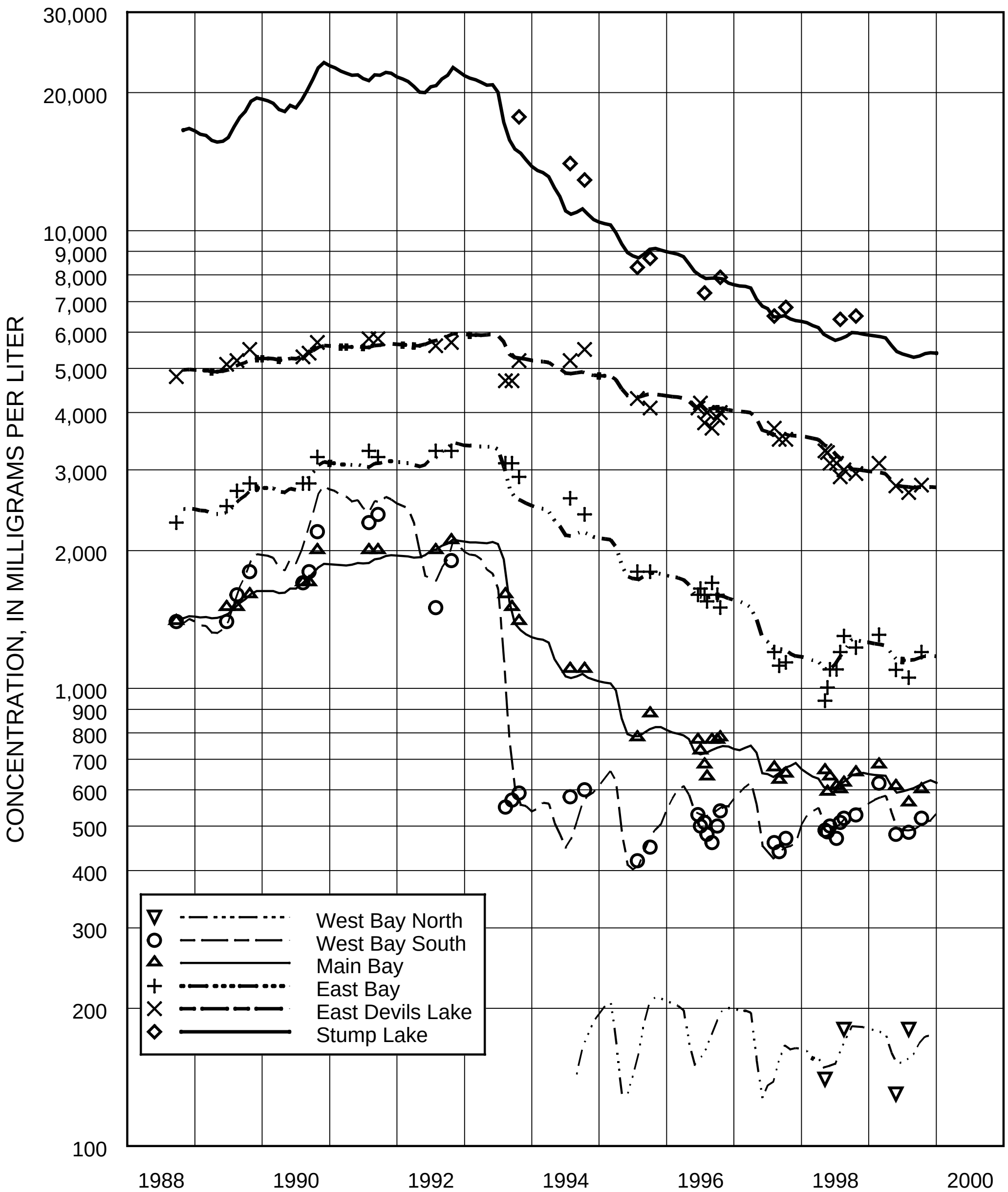

Figure 26. Recorded and fitted dissolved sulfate concentrations for Devils Lake and Stump Lake for 1988-99 from regression model with sediment interaction and mixing between lake boxes. (Symbols indicate recorded concentrations, and lines indicate fitted concentrations.)

sulfate to migrate from east to west. For all three connections, significant amounts of sulfate are moving from east to west because of wind-induced (indicated by negative fluxes during April through November) and buoyancy-induced (indicated by negative fluxes during December-March) exchange flows. As shown in figure 29, negative fluxes between West Bay and Main Bay tend to be greater during ice-cover conditions than during open-water conditions. However, for the other two connections, negative fluxes tend to be somewhat greater during open-water conditions.

Large fluxes of sulfate occurred from East Bay to Main Bay during 1997 and from East Devils Lake to East Bay during 1998. As discussed previously, these fluxes were caused by submergence of the Highways 20 and 57 bridges in 1997 and Woods Rutten Road in 1998. Because of the submergence, fluxes during those years were increased to more closely match the estimated sulfate loads shown in figure 27. The effect from submergence of Woods Rutten Road was particularly evident as shown by the large decrease in sulfate load for East Devils Lake and the corresponding increase in sulfate load for East Bay during 1998 (fig. 27).

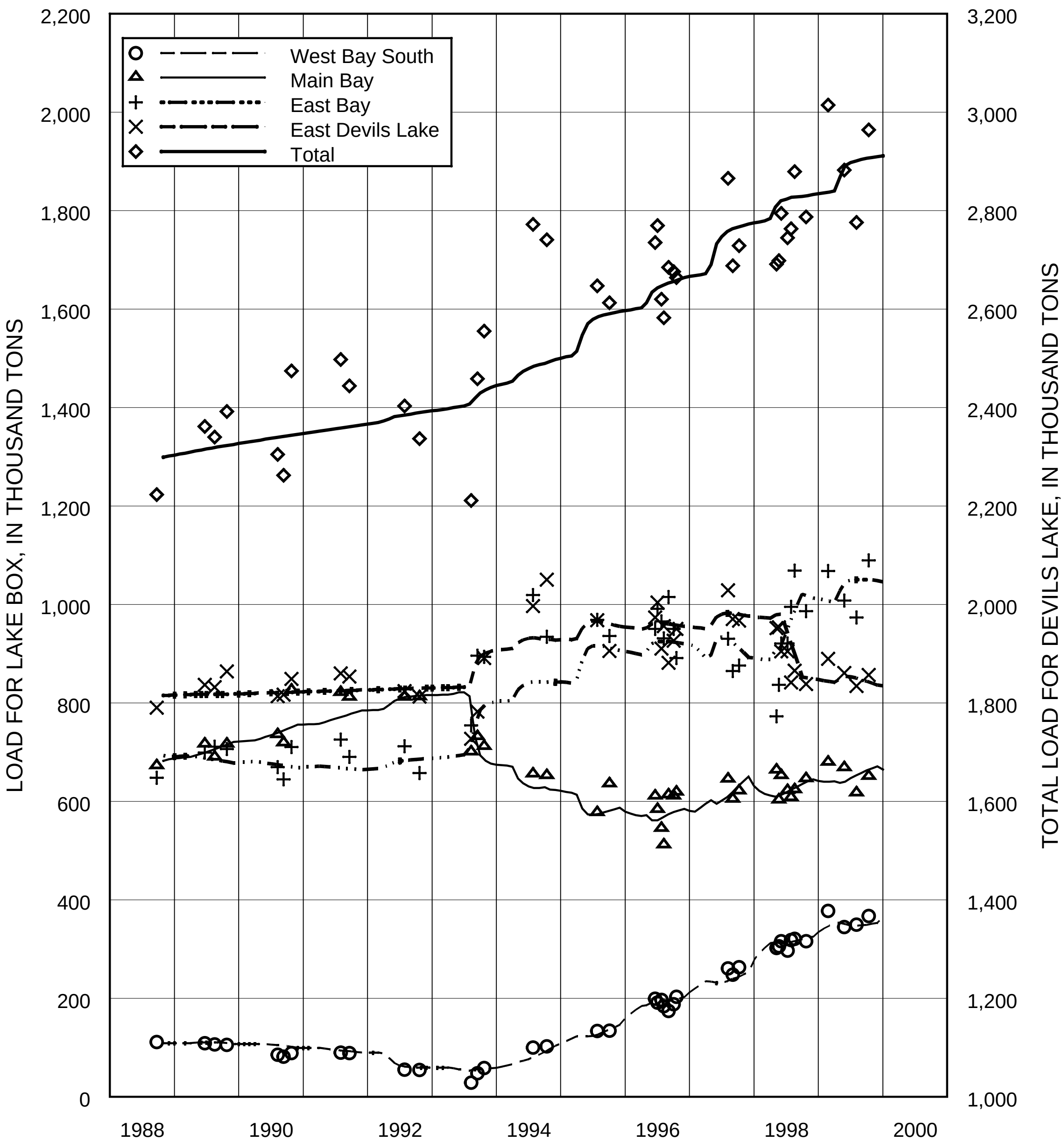

Figure 27. Estimated and fitted dissolved sulfate loads for Devils Lake for 1988-99 from regression model with sediment interaction and mixing between lake boxes. (Symbols indicate estimated loads computed from recorded concentrations, and lines indicate fitted loads.)

OUTLET SIMULATION MODEL

The detailed water and sulfate mass-balance models described previously were modified to include an outlet from Devils Lake to the Sheyenne River. The outlet simulation model is described in this section using a hypothetical sequence of future precipitation, evaporation, and inflow data for Devils Lake. In the hypothetical sequence of data, referred to as the “wet scenario", Devils Lake continues to rise and spill to the Sheyenne River if no outlet is constructed. Various outlet alternatives were evaluated for reducing flood damages under the wet scenario. A later section of this report details a statistical time-series model developed to generate future precipitation, evaporation, and inflow data for the outlet simulation model. Thus, the outlet alternatives can be evaluated for virtually any conceivable future scenario.

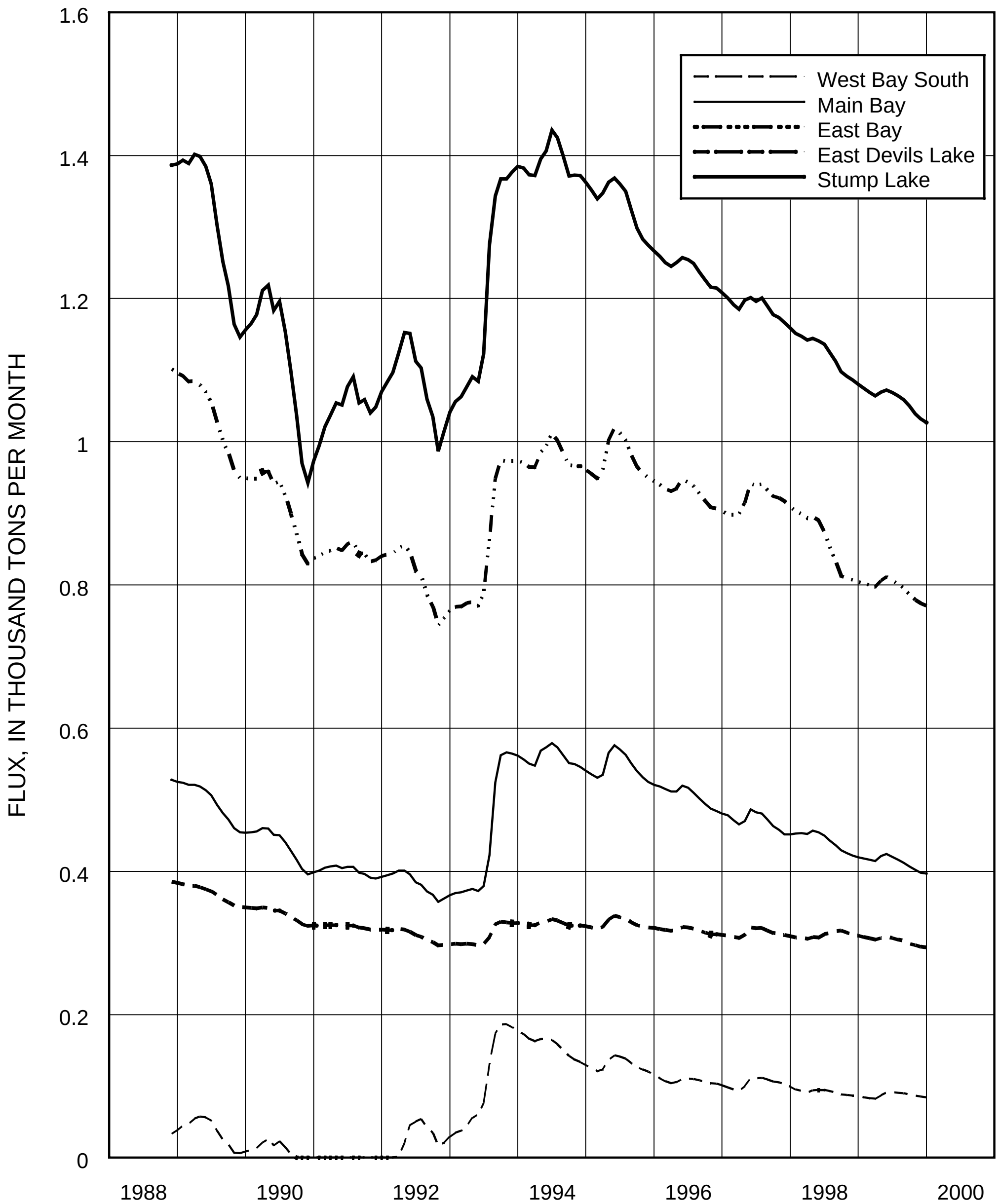

Figure 28. Estimated flux of sulfate from bottom sediments to lake boxes for Devils Lake and Stump Lake for 1988-99.

Ambient Streamflows and Sulfate Concentrations for the Sheyenne River

The amount of water discharged from Devils Lake under the various outlet alternatives depends on the ambient (without-outlet) streamflow and sulfate concentrations for the Sheyenne River receiving waters. Daily streamflow data and recorded water-quality data are available for gaging station 05056000 (Sheyenne River near Warwick, N. Dak.; site 24, fig. 2), which is downstream of the proposed Peterson Coulee insertion point, but no data are available for the insertion point. Therefore, to simulate daily streamflow at the insertion point, streamflows for the Sheyenne River near Warwick were multiplied by 0.77, which is the ratio of the contributing drainage area upstream of Peterson Coulee to the contributing drainage area upstream of station 05056000 (Daniel Reinartz, U.S. Army Corps of Engineers, oral commun., 2000). Daily sulfate concentrations for the Sheyenne River near Warwick then were generated given the daily streamflow data. The regression model that relates sulfate concentration to daily streamflow for the Sheyenne River near Warwick on the basis of recorded data for 1970-99 is given by

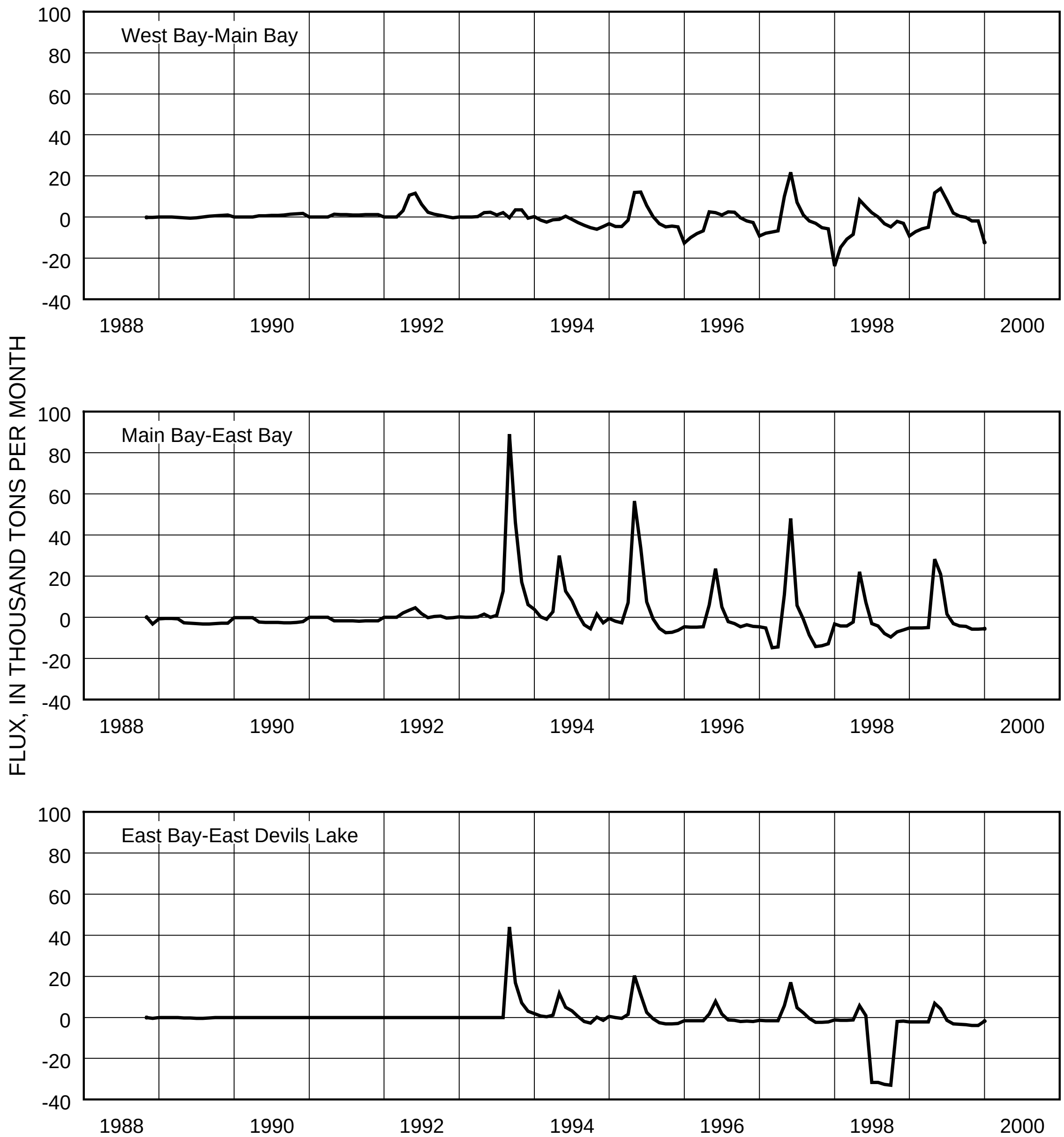

Figure 29. Estimated flux of sulfate between lake boxes for Devils Lake for 1988-99.

$$\log(C_W) = (2.047 + 0.031A - 0.128B) + (0.061 + 0.054A - 0.116B)X - (0.170 + 0.095A + 0.029B)X^2 + e \quad (34)$$

where

C_W is the sulfate concentration for the Sheyenne River near Warwick, in milligrams per liter;

A is the cosine of $2\pi\tau$, where τ is time, in decimal years, and $\tau = 0$ corresponds to October 1, 1970;

B is the sine of $2\pi\tau$;

X is $\log(Q_W) - 1.24$, where Q_W is the mean daily streamflow, in cubic feet per second; and

e is the residual.

The recorded and fitted sulfate concentrations for the Sheyenne River near Warwick for water years 1971-99 are shown in figure 30. As indicated by the cosine and sine terms in equation 34, significant seasonality existed in the intercept and in the coefficients for the linear and quadratic terms in X. The coefficient of determination for equation 34 was 46 percent, and the standard error was 0.15 in logarithmic units. Standard residual diagnostics indicated the residuals were approximately normally distributed, uncorrelated, unbiased, and had constant variance, but the relatively low coefficient of determination indicated that a high degree of noise remained in the residuals. Thus, because the fitted concentrations may severely underestimate the recorded concentrations, especially during May through August when the proposed outlet would be operating (fig. 30), a procedure for generating concentrations that included random noise needed to be developed.

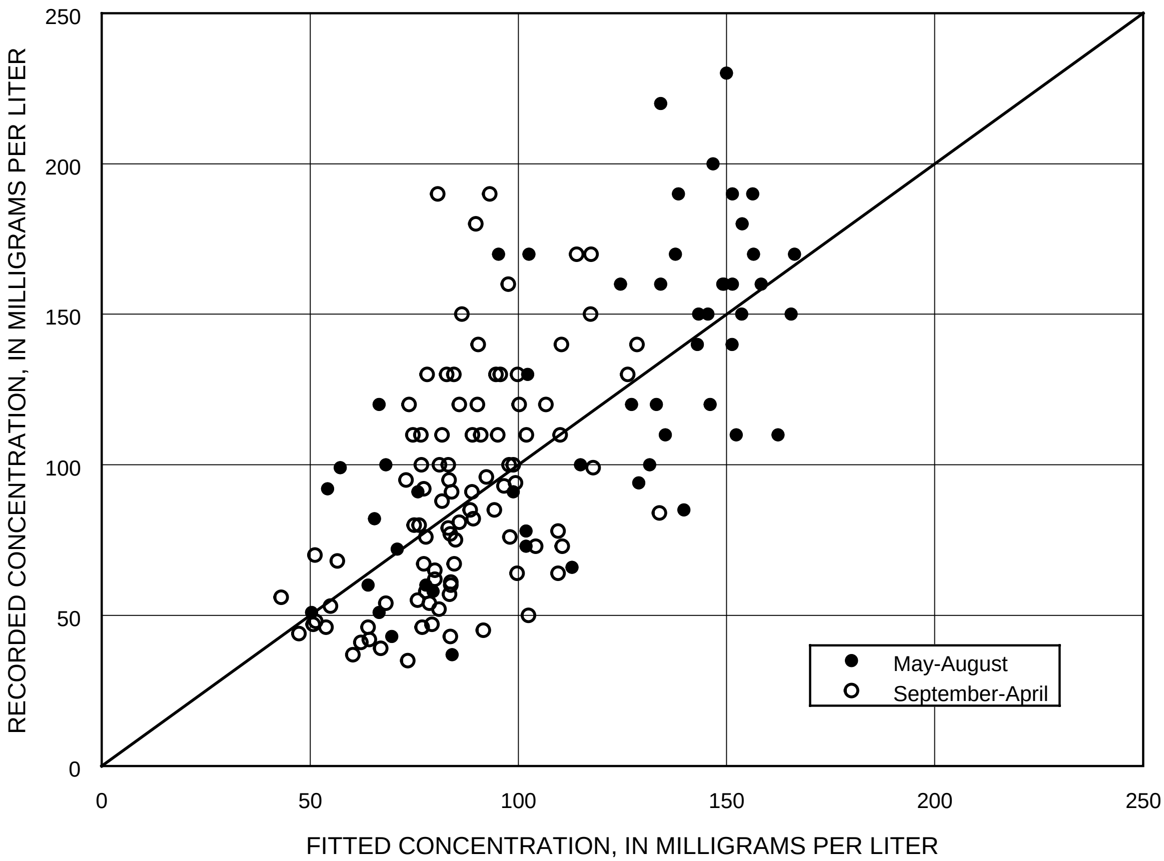

Figure 30. Recorded and fitted dissolved sulfate concentrations for the Sheyenne River near Warwick for water years 1971-99 from regression model. (Line indicates line of equality between recorded and fitted values.)

Generation of realistic concentrations on a daily time step requires knowledge of the properties of the residuals on the same time step. Because successive recorded concentrations used to fit the regression model (eq. 34) generally were separated by at least 30 days, the residuals from the regression model could not be used to directly infer the correlation between residuals from one day to the next. For example, if equation 34 was used to generate sulfate concentrations for 2 successive days, and the values of the random noise ($e1$ and $e2$) were assumed to be independent normal random variables with a mean of zero and a standard deviation of 0.15 (the standard error of the regression), the resulting concentration on the first day easily could be (depending on the values of $e1$ and $e2$) two or three times higher (or lower) than the concentration on the second day. Such variation in concentrations on a daily time step is unrealistic. Therefore, to generate realistic concentrations on a daily time step, the random noise in log-transformed daily sulfate concentrations was generated using the following equation:

$$e_1 = 0.15z_1; \; e_t = 0.95e_{t-1} + 0.15(1 - 0.95^2)^{0.5} z_t, \; t = 2, 3, \; ..., \tag{35}$$

where

e_t is the random noise for day t; and

z_t is a sequence of independent, standard normal random variables.

The standard deviation of the noise generated using equation 35 was 0.15 (the same as the standard error for the regression model), and the correlation between generated daily noise values separated by more than 1 month was near zero. However, the correlation between values separated by 1 day was 0.95. Thus, the differences between the values of the noise from one day to the next tended to be small. Daily sulfate concentrations generated using equations 34 and 35 generally differed by less than 10 percent from one day to the next. The daily sulfate concentrations, including noise, for water years 1971-99 are shown in figure 31. The generated concentrations reproduced the seasonal variation evident in the

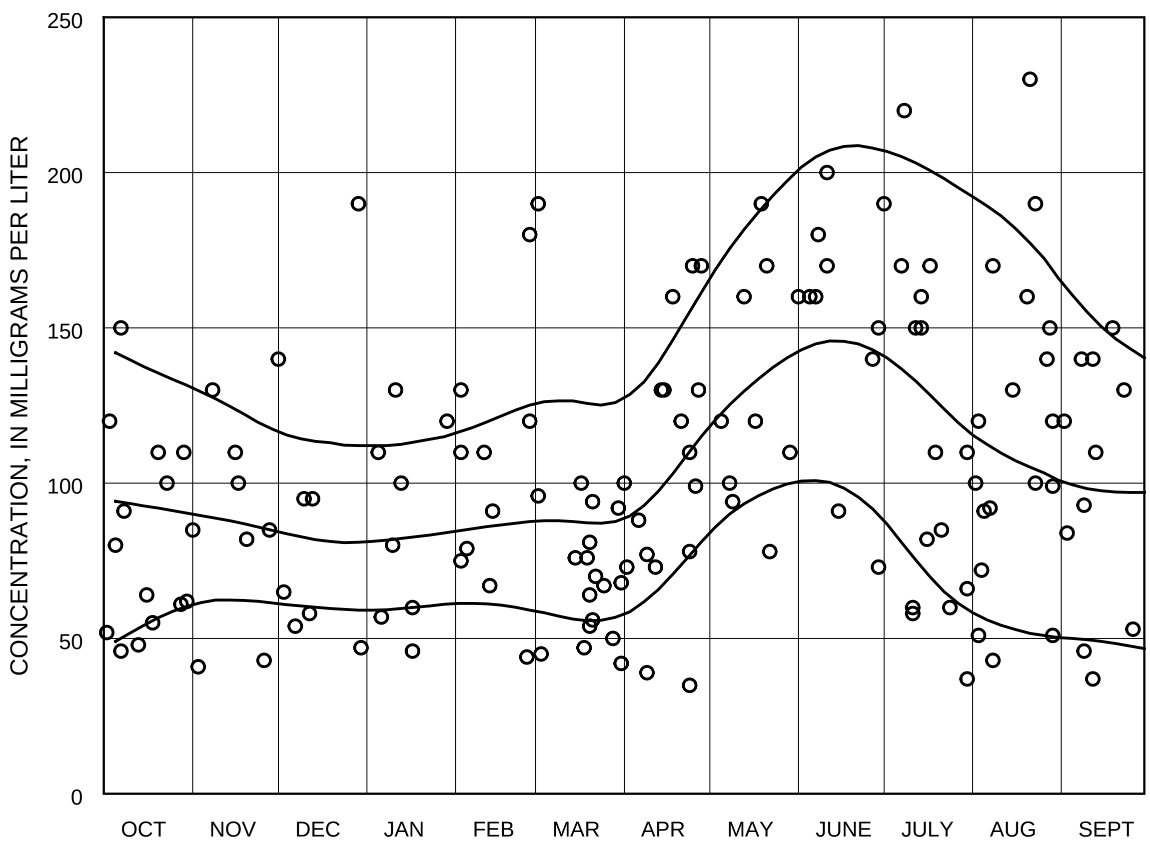

Figure 31. Recorded dissolved sulfate concentrations for the Sheyenne River near Warwick for water years 1971-99 and percentiles of generated concentrations. (Circles indicate recorded concentrations, top line indicates 90th percentile, middle line indicates 50th percentile, and bottom line indicates 10th percentile.)

recorded concentrations. Concentrations tended to be highest, and most variable, during May through August, and more than 10 percent (and up to almost 50 percent) of the generated concentrations exceeded 150 milligrams per liter during those months. Generated concentrations for the other months tended to vary between 50 and 150 milligrams per liter.

The potential outlet discharge will be constrained so the sulfate concentration for the combined Sheyenne River streamflow and outlet discharge will not exceed a predetermined upper limit. Therefore, because recorded sulfate concentrations for the Sheyenne River at the Peterson Coulee insertion point are not available, daily concentrations at the insertion point were assumed to be the same as generated daily concentrations for the Sheyenne River near Warwick. The rationale for this assumption is as follows. If outlet discharge at the Peterson Coulee insertion point is constrained using 77 percent of the streamflow near Warwick and the same daily sulfate concentration as near Warwick, the sulfate concentration for the combined Sheyenne River streamflow and outlet discharge should be less than the sulfate constraint because more streamflow is available near Warwick than at the insertion point to dilute the outlet discharge. As long as the ambient sulfate concentration near Warwick is less than the sulfate constraint (which is almost always the case), the sulfate constraint near Warwick will not be exceeded. However, the sulfate constraint could be exceeded at the insertion point if the sulfate concentration for the Sheyenne River at that location is larger than the concentration near Warwick.

Outlet Discharge

The modified water and sulfate mass-balance models were used along with daily streamflow and sulfate concentrations for the Sheyenne River receiving waters to compute outlet discharge. For example, one of the outlet alternatives is to pump water from West Bay, near the town of Minnewaukan, through a constructed pipeline into Peterson Coulee (fig. 2). For this alternative, the water and sulfate mass-balance equations for West Bay (eqs. 5 and 14) were modified as follows:

$$V'_1(t) = V_1(t) - Q_P(t) \tag{36}$$

$$S'_1(t) = S_1(t) - Q_P(t)C_P(t) \tag{37}$$

where

$V'_1(t)$ is the volume of West Bay South with the outlet at the end of month t, in acre-feet;

$V_1(t)$ is the volume of West Bay South computed using equation 5, in acre-feet;

$Q_P(t)$ is the outlet discharge for month t, in acre-feet;

$S'_1(t)$ is the sulfate load for West Bay South with the outlet at the end of month t, in tons;

$S_1(t)$ is the sulfate load for West Bay South computed using equation 14, in tons; and

$C_P(t)$ is the sulfate concentration for the outlet discharge, in tons per acre-foot.

The volume, $V_1(t-1)$, and sulfate load, $S_1(t-1)$, given in equations 5 and 14 correspond with the volume, $V'_1(t-1)$, and sulfate load, $S'_1(t-1)$, calculated by equations 36 and 37 for the previous month. Although the addition of an outlet changes the flows between lake boxes (the Q_{ij}'s) and, thus, changes the volumes and sulfate concentrations for all lake boxes--not just West Bay--the equations for the remaining boxes are not included in this report. Rather, the numerical algorithm used to compute the modified volumes and sulfate loads for those boxes, including the outlet, is described in the following paragraphs.

To simplify computation of the outlet discharge, the sulfate concentration for the discharge for month t was assumed to be the same as the sulfate concentration for the appropriate lake box at the end of the previous month. Thus, for the West Bay outlet,

$$C_P(t) = \frac{V_1(t-1)}{S_1(t-1)}. \tag{38}$$

Using this assumption, the computed sulfate concentration for the outlet discharge may be slightly higher than the actual concentration during months when in-lake concentrations are decreasing and slightly lower than the actual concentration during months when in-lake concentrations are increasing. However, because in-lake concentrations change relatively slowly through time, the differences between computed and actual concentrations as a result of this assumption should not be substantial. As a sensitivity analysis, results of model simulations using this assumption were compared to results of model simulations using the assumption that pumping from West Bay occurs after precipitation, evaporation, external inflow (inflow from Big Coulee and Channel A and ungaged inflow), and flow between lake boxes has occurred for the month. Results of the simulations were nearly identical, indicating that the use of equation 38 to compute the sulfate concentration for the outlet discharge should not affect conclusions obtained from the simulations.

The outlet discharge for a particular month is the sum of the daily outlet discharges for the month and is given by

$$Q_P(t) = 1.98\Sigma_i Q_{Pi}(t) \quad (39)$$

where

Σ_i denotes the summation of daily outlet discharges for month t; and

$Q_{Pi}(t)$ is the outlet discharge for the ith day of month t, in cubic feet per second.

The outlet discharge for a particular day needed to satisfy three constraints related to pump capacity, downstream channel capacity, and downstream sulfate concentration. Thus,

$$Q_{Pi}(t) = \mathrm{Min}\{PC, CCD, SCD\} \quad (40)$$

where

PC is the pump capacity, in cubic feet per second;

CCD is the channel-constrained outlet discharge, in cubic feet per second; and

SCD is the sulfate-constrained outlet discharge, in cubic feet per second.

The value of PC was fixed in advance. However, the constrained discharges, CCD and SCD, depended on the ambient streamflow and sulfate concentration of the Sheyenne River on the particular day. An analysis by the North Dakota State Water Commission (1997) indicated that a streamflow of 600 cubic feet per second downstream of the Peterson Coulee insertion point should not contribute significantly to overbank flooding downstream. Therefore, the channel-constrained discharge is given by

$$CCD = \mathrm{Max}\{0, 600 - Q_{Si}(t)\} \quad (41)$$

where

$Q_{Si}(t)$ is streamflow for the Sheyenne River for the ith day of month t, in cubic feet per second.

To ensure that the sulfate concentration for the combined ambient Sheyenne River streamflow and outlet discharge was less than a predetermined maximum value, the value of SCD was computed using the following equation:

$$\frac{[Q_{Si}(t)C_{Si}(t) + SCD(735C_P(t))]}{[Q_{Si}(t) + SCD]} = CMAX \quad (42)$$

where

$C_{Si}(t)$ is the sulfate concentration for streamflow for the Sheyenne River for the ith day of month t, in milligrams per liter;

$C_P(t)$ is the sulfate concentration for the outlet discharge, in tons per acre-foot; and

$CMAX$ is the sulfate constraint for the Sheyenne River, in milligrams per liter.

The factor, 735, in equation 42 converts concentration in tons per acre-foot to concentration in milligrams per liter.

On any given day when the proposed outlet was operating, the daily outlet discharge was determined by equation 40. If the outlet was not allowed to operate on a particular day, the outlet discharge for that day was set equal to zero. Criteria for determining when the outlet could operate are described later.

After the outlet discharge for a given month was computed and given the starting volumes and sulfate loads for each lake box at the end of the previous month, the outlet discharge (and associated sulfate load) was removed from the appropriate box. The given month's flows between the boxes, the sulfate loads for the boxes, the flux of sulfate from bottom sediments, and the mixing between the boxes then were computed as described previously.

Simulation Results for Wet Scenario

The outlet simulation model was used to determine the effects of several proposed outlet alternatives on in-lake and downstream water quantity and water quality. The model was used with a hypothetical future sequence of data, referred to as the "wet scenario" (U S. Army Corps of Engineers, 2002), in which monthly precipitation and evaporation values, inflow from Big Coulee and Channel A, and ungaged inflow for water years 2001-50 (October 1, 2000, to September 30, 2050) were assumed to be the same as recorded monthly values for the following sequence of water years:

{1993-99, 1993-99, 1993-99, 1981-99, 1981-90}.

Thus, wet conditions similar to those that occurred during 1993-99 were assumed to occur in the future, back to back, for 21 years. The remaining 29 years of the 50-year simulation period consisted of a repeat of conditions that occurred during 1981-99 (19 years) and during 1981-90 (10 years). The future represented by the wet scenario is one in which a potential outlet could be most effective for reducing flood damages and minimizing adverse effects on downstream water quality. Thus, the wet scenario provides a useful basis for screening outlet alternatives because alternatives that are not economically viable and environmentally acceptable (as determined by the Corps' criteria) for that scenario probably would not be acceptable for most other conceivable scenarios. The wet scenario also provides a useful scenario for evaluating the effects of a potential uncontrolled natural spill on downstream water quantity and water quality.

Starting values for the outlet simulation model for October 1, 2000 (the first day of the simulation period) are given in table 7. The starting lake levels for that date were set equal to known values for that date, and the starting in-lake sulfate

Table 7. Starting values for outlet simulation model for October 1, 2000

Lake box	Starting lake level (feet above sea level)	Starting sulfate concentration (milligrams per liter)
West Bay North	1,446.0	290
West Bay South	1,446.0	570
Main Bay	1,446.0	630
East Bay	1,446.0	1,200
East Devils Lake	1,446.0	2,650
Stump Lake	1,409.3	5,200

concentrations were approximated using concentrations measured by the North Dakota Department of Health (NDDH) in September 2000 (Scott Elstad, North Dakota Department of Health, written commun., 2001). Starting values for the sulfate loads for the sediment boxes (eq. 27) were set equal to the values obtained from the sulfate mass-balance model at the end of the model calibration period (December 31, 1999). Values for the sulfate loads were required by the model to compute the future flux of sulfate from bottom sediments.

Several assumptions were inherent in the simulation results given in this report, and violation of any of the assumptions could result in significant differences between the simulated outlet performance and the actual outlet performance. For example, the assumption was made that Highway 57, Grahams Island Road, and Woods Rutten Road would continue to be raised to prevent submergence if Devils Lake continues to rise. If any of the roads are submerged, movement of sulfate from east to west could increase and cause sulfate concentrations in the west end of the lake and, thus, in the outlet discharges to increase. Simulation results would be significantly different if Highway 57 is submerged because the highway is particularly important for controlling mixing between East Bay and Main Bay. Results would not be as significantly different if Grahams Island Road is submerged because mixing between Main Bay and West Bay already is occurring at Ziebach Pass. However, if Grahams Island Road is submerged, some inflow to West Bay South could flow directly into Main Bay, bypassing the normal flow route through Ziebach Pass and, thus, affect the water quality of West Bay South.

Other assumptions inherent in the simulation results were that the levees that protect the city of Devils Lake and the surrounding areas would continue to be raised to prevent overflow and that the hydrologic characteristics and land use in the upper Devils Lake and Sheyenne River Basins would remain relatively unchanged from conditions that presently exist. If the levees are breached, the elevation-area-volume relations of the lake boxes would change and the water mass-balance computations would be affected. Major changes in the hydrologic characteristics or the land use could change the water quality of basin runoff and, thus, affect in-lake or downstream sulfate concentrations.

The Corps has considered many alternatives for a potential outlet (U S. Army Corps of Engineers, 2002). For this report, four of the alternatives (table 8) were selected to illustrate the outlet simulation model. Of the alternatives given in

Table 8. Alternatives selected to illustrate outlet simulation model

[These alternatives, along with other alternatives not shown in this report, were developed by the U.S. Army Corps of Engineers, 2002]

Alternative	Water source	Assumptions regarding Channel A, Highway 19, and Highway 57
A1. West Bay outlet	West Bay (south of Highway 19)	Channel A--No change from existing condition. Highway 19--No change from existing condition. Highway 57--No change from existing condition.
A2. Modified West Bay outlet	West Bay (south of Highway 19)	Channel A--Flow is diverted through the chain of lakes into Big Coulee unless the total inflow from Big Coulee and Channel A exceeds 2,000 cubic feet per second. If the total inflow exceeds 2,000 cubic feet per second, excess water is allowed to flow into Main Bay. Highway 19--No change from existing condition. Highway 57--Measures are taken to prevent wind- and buoyancy-induced exchange flows at the Highway 57 bridge.
B1. Pelican Lake outlet	Pelican Lake (north of Highway 19)	Channel A--Same assumptions as for alternative A2. Highway 19--Measures are taken to prevent significant submergence of the highway embankment and to prevent mixing between West Bay and Pelican Lake. However, the highway is not used to control lake levels. Highway 57--Same assumptions as for alternative A2.
B2. Modified Pelican Lake outlet	Pelican Lake (north of highway 19)	Channel A--Same assumptions as for alternative A2. Highway 19--When lake levels are less than 1,454.0 feet above sea level, the highway is used to control the flow of water from south to north. When lake levels exceed 1,454.0 feet above sea level, the assumptions are the same as those for alternative B1. Highway 57--No change from existing condition.

table 8, the West Bay outlet (alternative A1) is the easiest and least costly to implement. However, water-quality constraints in the Sheyenne River often reduce the amount of water that can be discharged for this alternative (U.S. Army Corps of Engineers, 2002). The remaining alternatives become more difficult and costly to implement but progressively increase the amount of water that can be discharged. Thus, the water-quality constraints in the Sheyenne River become progressively less restrictive on outlet discharges.

For the modified West Bay outlet (alternative A2) and for both Pelican Lake outlets (alternatives B1 and B2), fresh water that normally would enter Main Bay through Channel A is assumed to be diverted through the original (pre-1979) flow path into West Bay north of Highway 19. If total inflow from Big Coulee and Channel A exceeds 2,000 cubic feet per second, excess water is allowed to flow into Main Bay to alleviate the potential for severe flooding north of Highway 19. In alternatives A2 and B1, the assumption also is made that measures are taken to prevent wind- and buoyancy-induced exchange flows at the Highway 57 bridge. Measures to prevent, or at least greatly reduce, these exchange flows would be relatively easy to implement (Bruce Engelhardt, North Dakota State Water Commission, oral commun., 2001). To incorporate the assumption in the model, the mixing coefficient, m_2, in equation 33 was set equal to zero.

Alternatives B1 and B2 differ according to future actions assumed for Highway 19. In alternative B1, Highway 19 is not reinforced to serve as a dam to control lake levels. However, the assumption is made that measures are taken to prevent significant submergence of the highway embankment if Devils Lake rises above the existing minimum roadway elevation of 1,455.0 feet above sea level. The measures, which may include the addition of fill and riprap where required to ensure that flow is restricted primarily to the existing bridge opening between West Bay and Pelican Lake, would be taken to prevent the enhanced mixing of the relatively fresh water north of the highway and the more saline water south of the highway.

In alternative B1, as pumping occurs, the lake level north of Highway 19 may recede below the lake level south of Highway 19 and water may flow from south to north, causing an increase in sulfate concentrations for the outlet discharge. In alternative B2, Highway 19 is reinforced to serve as a dam to control the flow of water from south to north when the level of Devils Lake is less than 1,454.0 feet above sea level. However, when inflow causes the lake level north of the highway to exceed the lake level south of the highway, water is allowed through the control structure to prevent the lake level north of the highway from rising more than 0.1 foot above the lake level south of the highway. When the level of Devils Lake exceeds 1,454.0 feet above sea level, the control structure is not operated and the same measures as those described for alternative B1 are used to prevent mixing between West Bay and Pelican Lake. The minimum lakebed elevation of Pelican Lake is about 1,430 feet above sea level. However, when pumping causes the level of the lake to recede below 1,440 feet above sea level, water is allowed to flow from West Bay to Pelican Lake to maintain a pool elevation of 1,440 feet above sea level. Thus, the maximum head differential between West Bay and Pelican Lake is 14 feet (when West Bay is at 1,454 feet above sea level and Pelican Lake is at 1,440 feet above sea level).

Operational constraints provided by the Corps (U.S. Army Corps of Engineers, 2002) for evaluation of the outlet alternatives are given in table 9. The pump capacity ranges from 300 to 480 cubic feet per second. Pump capacities less than 300 cubic feet per second were considered too small for effective flood control, and pump capacities greater than 480 cubic feet per second were considered too costly and difficult to implement. The pumping window (the days during which pumping is allowed) is May 1 through November 30 each year so pumping is not allowed during winter ice cover. The channel capacity of the Sheyenne River below the outlet insertion point is 600 cubic feet per second. Thus, to avoid significant contribution of outlet discharge to overbank flooding downstream, outlet discharge is reduced whenever the combined ambient Sheyenne River streamflow and outlet discharge exceeds 600 cubic feet per second. To prevent the outlet from contributing to excessive lake-level declines during drought conditions, the pumps are assumed to operate only when the level of Devils Lake is greater than the trigger elevation of 1,441.4 feet above sea level. The lowest Sheyenne River sulfate constraint is 250 milligrams per liter. Based on downstream flow-routing models developed by the Corps, a 250-milligram-per-liter constraint should not result in substantial increases in the frequency of exceedances of water-quality standards in the Sheyenne and Red Rivers. The highest sulfate constraint is 450 milligrams per liter, which is the sulfate standard for the Sheyenne River (North Dakota State Department of Health and Consolidated Laboratories, 1991). However, a sulfate constraint of 450 milligrams per liter may result in substantial increases in the frequency of exceedances of water-quality standards in the Red River during certain times of the year (U.S. Army Corps of Engineers, 2002).

Table 9. Constraints for outlet operation

[From U.S. Army Corps of Engineers, 2002]

	Constraint
Pump capacity	Between 300 and 480 cubic feet per second
Pumping window	May 1 through November 30
Sheyenne River channel capacity	600 cubic feet per second
Sheyenne River sulfate constraint	Between 250 and 450 milligrams per liter
Starting date for Channel A diversion	October 1, 2002
Starting date for Highway 19 control structure	May 1, 2005
Starting date for Highway 57 mixing barrier	October 1, 2002
Starting date for outlet operation	May 1, 2005
Starting date for simulation	October 1, 2000
Trigger elevation	1,441.4 feet above sea level

The starting date for the outlet simulation analysis is October 1, 2000. However, because of the time needed to complete the environmental impact study for an outlet, obtain Congressional authorization for an outlet, and actually construct an outlet, the earliest feasible starting date for outlet operation is May 1, 2005 (U.S. Army Corps of Engineers, 2002). The Highway 19 control structure (if required) is assumed to be operational at the same time as the outlet. However, the Channel A diversion and the Highway 57 mixing barrier (if required) are assumed to be operational on October 1, 2002. Because these measures for freshening the west end of the lake are relatively easy to implement, an assumption was made that they would be in place shortly after authorization for an outlet is obtained. Keeping the west end of the lake as fresh as possible before the outlet is constructed would allow more water to be discharged from the outlet during the first few years of operation.

The baseline condition is the same for all outlet alternatives and refers to the case that none of the outlet features (including the Channel A diversion, Highway 19 control structure, and Highway 57 mixing barrier) are constructed. The changes likely to occur in the upper reaches of Tolna Coulee (near the Stump Lake-Tolna Coulee divide) in the event of a sustained natural spill from Stump Lake were evaluated to simulate discharges from Stump Lake for the wet scenario (U.S. Army Corps of Engineers, 2002) (see appendix A). Potential erosion of the Tolna Coulee channel is an important consideration for evaluating downstream effects of a natural spill. A qualitative description of the results of the evaluation is given in this section, and the procedure used in the evaluation is described in detail in appendix A.

Future lake levels of Devils Lake for the wet scenario baseline-condition simulation with and without erosion of the natural outlet from Stump Lake are shown in figure 32 along with daily streamflows for the Sheyenne River near Warwick (upstream of the confluence with Tolna Coulee) and discharge from Stump Lake to Tolna Coulee for January 1, 2015, to December 31, 2019. Lake levels for the existing natural outlet are the levels that would occur if erosion is prevented and the channel that currently exists is maintained. Lake levels for the eroded natural outlet are the levels that would occur if natural erosion is allowed. Stump Lake begins spilling in 2014 at a level of 1,459.0 feet above sea level. From the time of the first spill until June 2016, the spills are nearly identical for the existing and eroded natural outlets. During that period, a berm about 3,000 feet downstream of the Stump Lake-Tolna Coulee divide erodes, but the elevation of the divide remains at 1,459.0 feet above sea level. In June 2016, the divide begins to erode below 1,459.0 feet above sea level, and the spills are much larger than those for the existing natural outlet. The divide erodes quickly and within about 2 months is at an elevation of about 1,451 feet above sea level, 8 feet below the original elevation of the divide. The spills during that period increase to 6,000 cubic feet per second, and Devils Lake declines rapidly as large volumes of water spill. As Devils Lake declines, the outlet discharges decline until, at the end of 2017, Devils Lake is about 10 feet below the level it would have been at without erosion. The elevation of the divide reaches equilibrium at about 1,451 feet above sea level, and no further erosion of the divide occurs. However, a steep part of the Tolna Coulee channel about 15,000 feet downstream of

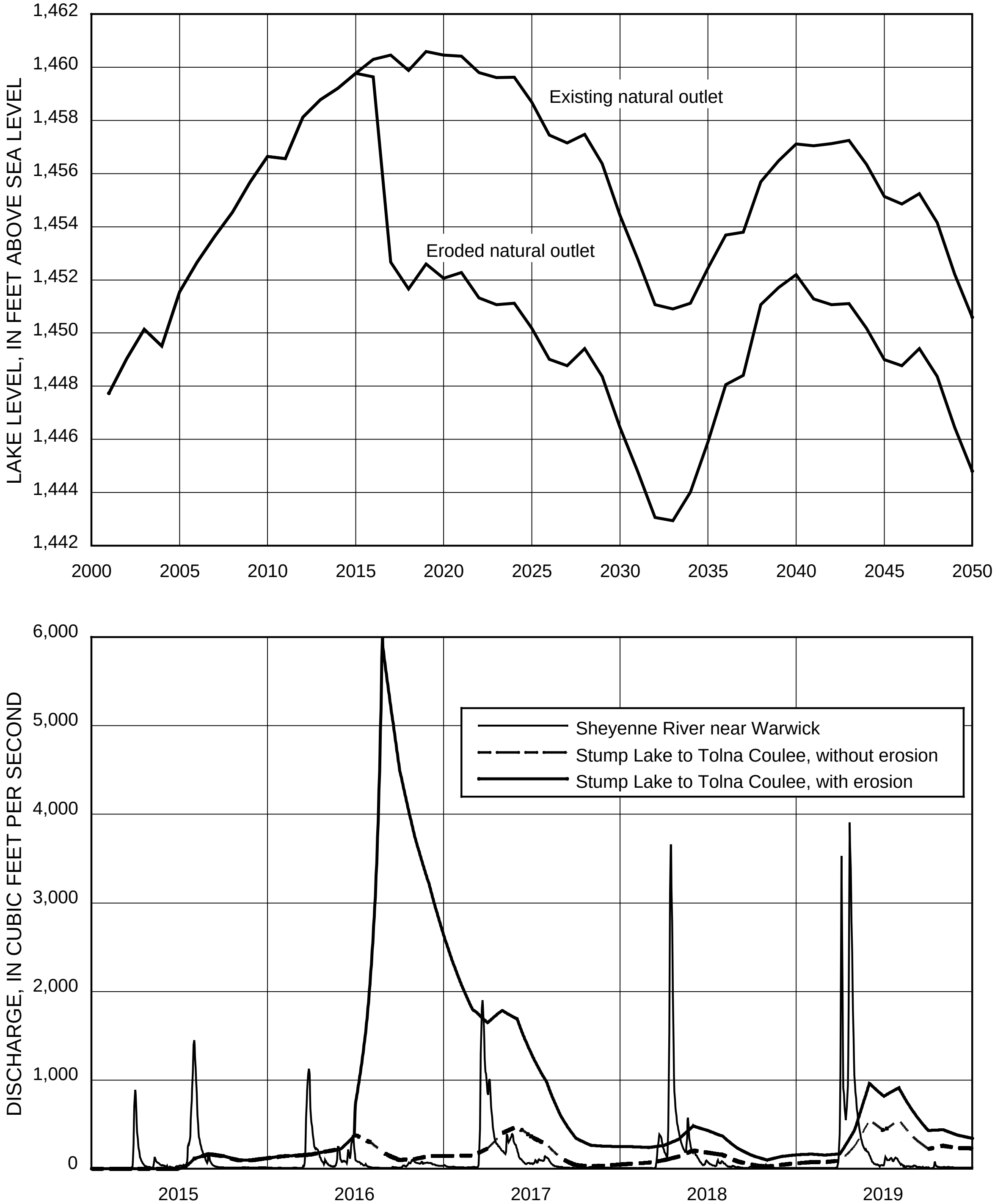

Figure 32. Results for wet scenario baseline (without-outlet) condition simulation with and without erosion of natural outlet. (Top graph indicates annual maximum lake levels of Devils Lake, and bottom graph indicates daily discharges.)

the divide continues to erode, and the flow velocities slowly increase until an ultimate equilibrium is reached (see appendix A).

Spills from Stump Lake remain below 500 cubic feet per second without erosion (fig. 32). Although the spills are not large compared to ambient streamflows for the Sheyenne River during spring runoff, the spills are much larger than typical summer and fall streamflow in the Sheyenne River. Furthermore, the water quality of the spills is much poorer than the water quality of ambient streamflows for the Sheyenne River. Therefore, the spills may cause significant water-treatment and channel-erosion problems downstream. With erosion, spills from Stump Lake during 2016 and 2017 would overwhelm ambient streamflows for the Sheyenne River in both volume and duration and cause extensive flooding that would have serious effects downstream, especially at Valley City and Fargo (U.S. Army Corps of Engineers, 2002).

In the remainder of this report, the baseline condition includes the assumption that no erosion of the natural outlet occurs. As indicated, if Devils Lake spills and natural erosion is allowed, the downstream effects of a spill probably would be much more severe than indicated by the simulation results.

Results for the wet scenario West Bay outlet (alternative A1) 450-milligram-per-liter sulfate constraint simulation with various pump capacities are shown in figure 33. Without an outlet, Devils Lake begins spilling to the Sheyenne River in 2014, rises to a peak level of 1,460.6 feet above sea level in 2019, and continues spilling until 2025. With a 300-cubic-foot-per-second pump capacity, Devils Lake reaches a peak level of 1,457.6 feet above sea level in 2021. Thus, the 300-cubic-foot-per-second pump capacity completely eliminates the natural spill and results in a peak lake level that is 3 feet less than the peak level for the baseline condition. With a 480-cubic-foot-per-second pump capacity, Devils Lake reaches a peak level of 1,454.0 feet above sea level in 2020, and the peak lake level is 6.6 feet less than the peak level for the baseline condition.

Increasing the pump capacity from 300 to 480 cubic feet per second results in significantly more control in terms of rising lake levels during wet conditions similar to those during 1993-99. According to Corps' estimates (U.S. Army Corps of Engineers, 2002), incremental flood damages or mitigation costs of $300 million (in present worth) would occur at lake levels between 1,454.0 and 1,457.6 feet above sea level. For example, levees that protect the city of Devils Lake would need to be raised, and Highways 19, 20, and 57 would need to be raised or allowed to overtop. Thus, if future conditions are similar to those in the wet scenario and if a 450-milligram-per-liter sulfate constraint is used, the added flood protection of a 480-cubic-foot-per-second pump capacity rather than a 300-cubic-foot-per-second pump capacity would be highly significant.

For the 450-milligram-per-liter sulfate constraint simulation, outlet discharges, even for the 480-cubic-foot-per-second pump capacity, are nearly equal to pump capacities from 2007 to 2024 (fig. 33). Thus, the 600-cubic-foot-per-second channel-capacity constraint is not exceeded to any extent during that period because ambient streamflow for the Sheyenne River from May through November seldom exceeds 120 cubic feet per second. For the same period (2007-24), the average sulfate concentration of the combined Sheyenne River streamflow and outlet discharge is less than 450 milligrams per liter, indicating the sulfate constraint does not reduce outlet discharge substantially during that period (fig. 33). However, the with-outlet concentrations for the Sheyenne River are substantially greater than the baseline concentrations. During 2026-50, the 450-milligram-per-liter sulfate constraint greatly reduces the outlet discharge for all three pump capacities. For the 480-cubic-foot-per-second pump capacity, the level of Devils Lake is less than the trigger elevation of 1,441.4 feet above sea level during 2032-33. Thus, no water is discharged from the outlet during that period.

If conditions during the next 20 years are similar to those during 1993-99, a pump capacity of at least 480 cubic feet per second may be required to control rising lake levels. However, if the sulfate constraint is more stringent than 450 milligrams per liter, the outlet discharge may decrease substantially. Results for the wet scenario West Bay outlet (alternative A1) 480-cubic-foot-per-second pump capacity simulation (fig. 34) indicate that the effectiveness of the West Bay outlet is greatly diminished for the 250- and 350-milligram-per-liter constraints. The outlet does not prevent an overflow in either case because the outlet discharges for those constraints are much less than those for the 450-milligram-per-liter constraint. Thus, because the 250- and 350-milligram-per-liter constraints usually are reached, the West Bay outlet alternative probably would not be effective for preventing an overflow when the sulfate constraint is less than 450 milligrams per liter.

The effects of a West Bay outlet on in-lake sulfate concentrations are shown in figures 35 and 36. Sulfate concentrations for the lake boxes for the wet scenario baseline condition (fig. 35) generally are indicated to decline during 2001-25 because of large freshwater inflows from Big Coulee and Channel A during that time. The resulting movement of water from west to east during 2001-25 tends to decrease concentrations and overcome evaporation and sediment flux, which tend to increase concentrations. However, because of the large surface area and relatively shallow depth of West Bay North, evaporation is a much higher percentage of the water balance for that lake box than for the other lake boxes, and concentrations in Pelican Lake slowly increase although lake levels are rising. The concentrations for East Devils Lake and Stump Lake decrease rapidly during 2001-05 when Stump Lake is filling as a result of outflow from East Devils

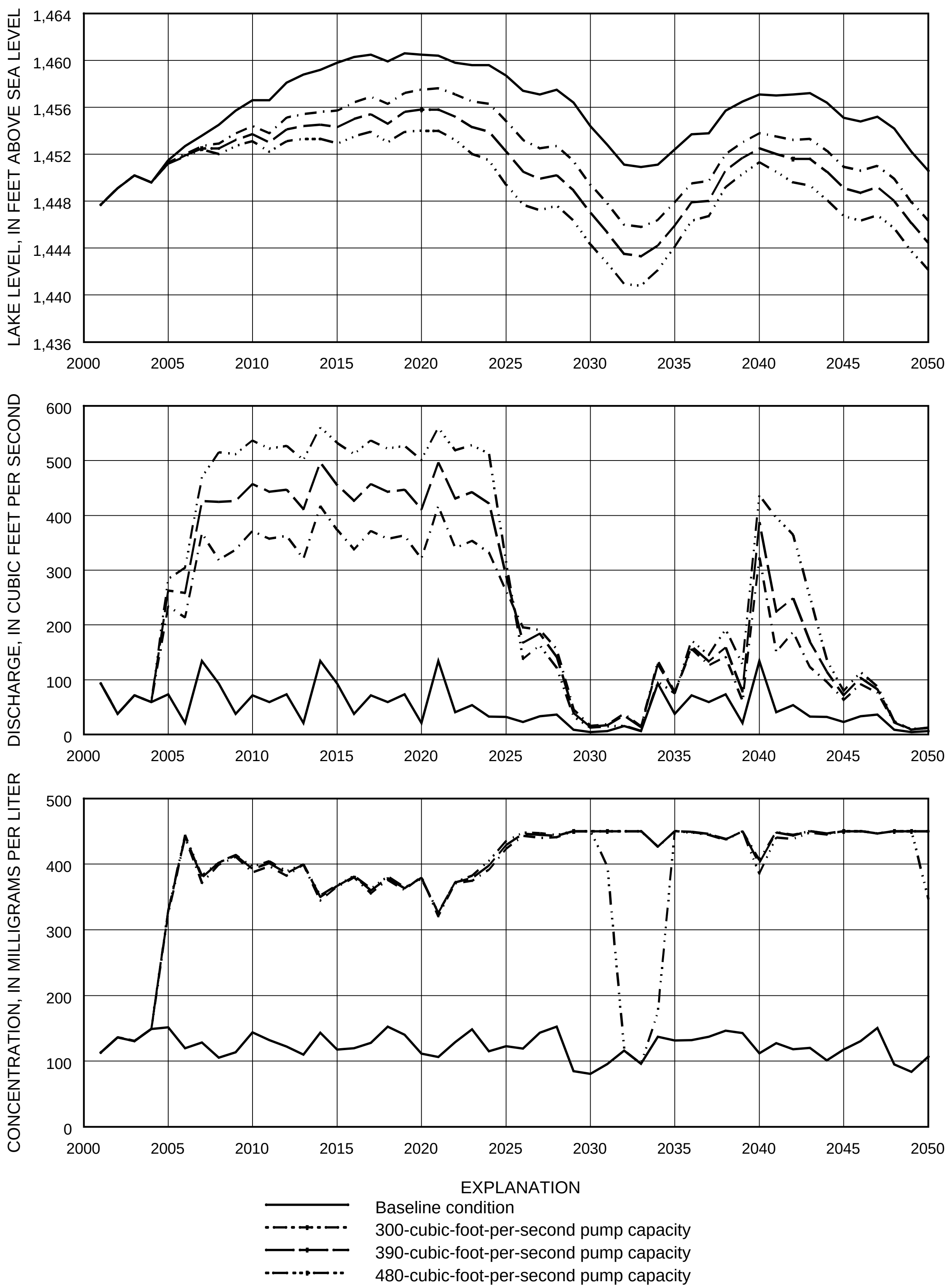

Figure 33. Results for water years 2001-50 for wet scenario West Bay outlet 450-milligram-per-liter sulfate constraint simulation. (Top graph indicates annual maximum lake levels of Devils Lake, middle graph indicates average daily discharge for the Sheyenne River below Peterson Coulee, and bottom graph indicates average daily sulfate concentration for the Sheyenne River below Peterson Coulee. Average daily values for the water year are for the pumping window, October through November and May through September.)

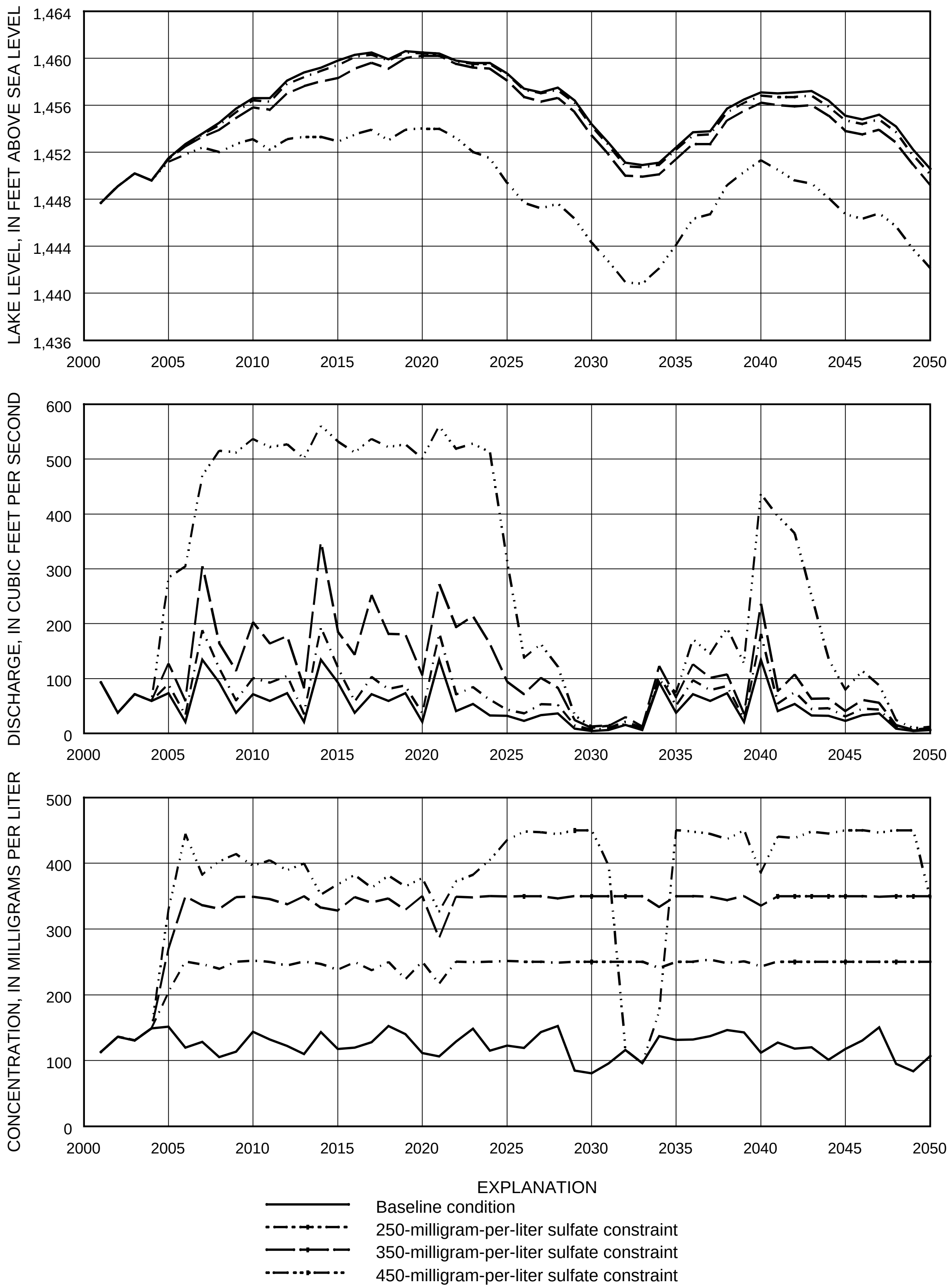

Figure 34. Results for water years 2001-50 for wet scenario West Bay outlet 480-cubic-foot-per-second pump capacity simulation. (Top graph indicates annual maximum lake levels of Devils Lake, middle graph indicates average daily discharge for the Sheyenne River below Peterson Coulee, and bottom graph indicates average daily sulfate concentration for the Sheyenne River below Peterson Coulee. Average daily values for the water year are for the pumping window, October through November and May through September.)

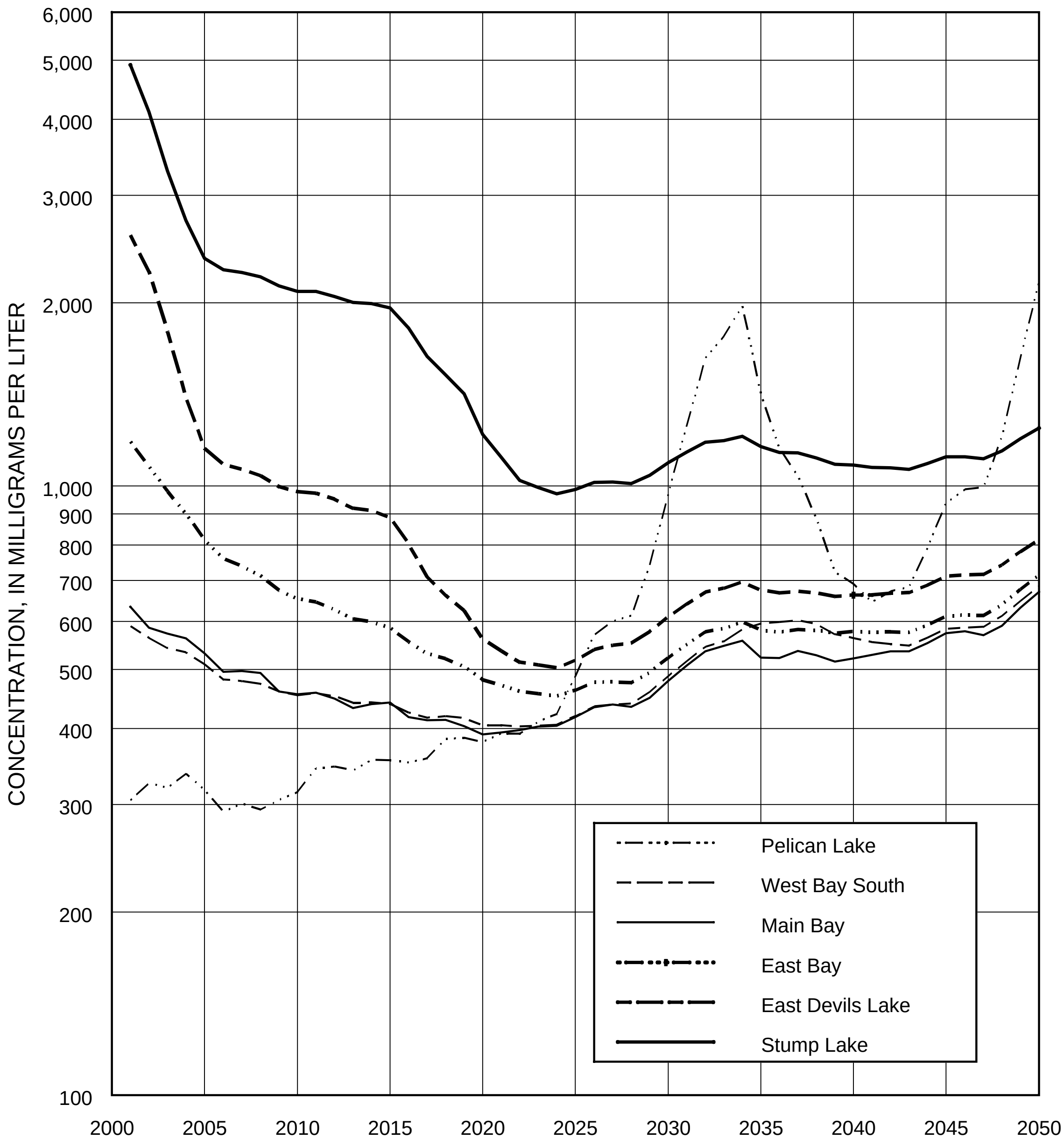

Figure 35. Average annual dissolved sulfate concentrations for Devils Lake for water years 2001-50 for wet scenario baseline condition.

Lake and during 2014-25 when Stump Lake is overflowing to the Sheyenne River. Stump Lake and Devils Lake become one water body in 2005, at a level of about 1,451.5 feet above sea level. Mixing between West Bay South, Main Bay, and East Bay is evident from the converging concentrations for those lake boxes (fig. 35). The concentrations generally increase during 2025-34 when lake levels are declining, but the concentrations in East Bay, East Devils Lake, and Stump Lake remain well below the concentrations at the beginning of the simulation period, and the concentrations in West Bay and Main Bay are only slightly higher than at the beginning of the simulation period. During long periods of lake-level declines, concentrations north of Highway 19 increase rapidly because of very little inflow or outflow and high evaporative losses. Conversely, the concentrations north of Highway 19 decrease rapidly during rapid lake-level rises. The volume of West Bay North is about 1.2 million acre-feet at a lake level of 1,460 feet above sea level and about 0.3 million acre-feet at a lake level of 1,450 feet above sea level. Therefore, the volume of that lake box in 2034 is only about one-fourth of its volume in 2021.

The with-outlet sulfate concentrations for Pelican Lake and West Bay South during 2005-24 (fig. 36) are slightly lower than the baseline concentrations (fig. 35) because the West Bay outlet causes more water to flow from Pelican Lake

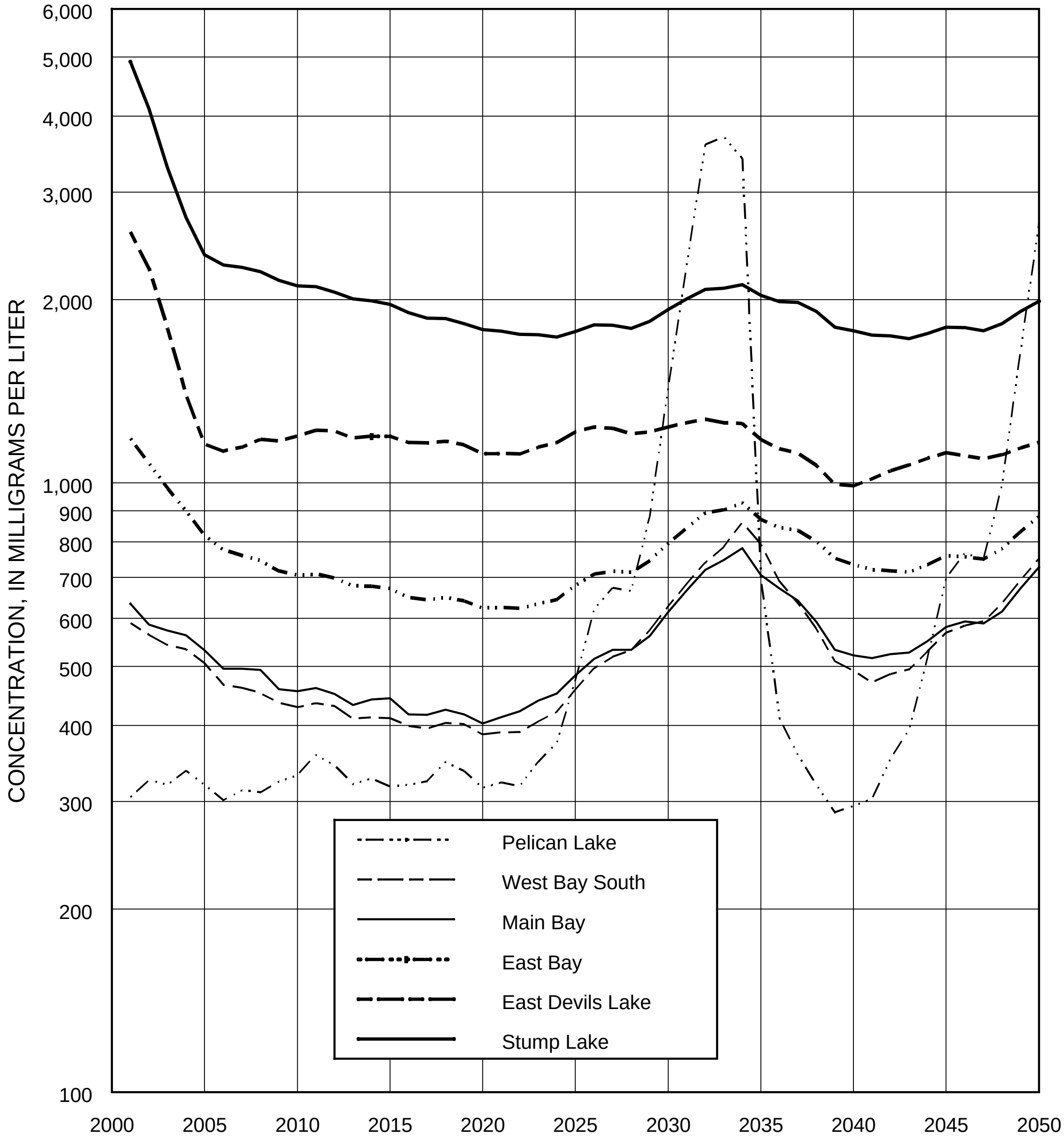

Figure 36. Average annual dissolved sulfate concentrations for Devils Lake for water years 2001-50 for wet scenario West Bay outlet 480-cubic-foot-per-second pump capacity simulation with 450-milligram-per-liter sulfate constraint.

to West Bay. Sulfate in Pelican Lake thus is removed from the lake and eventually discharged through the outlet (the removal of water from a lake box by pumping or outflow rather than by evaporation also removes sulfate from the lake box). The with-outlet and baseline concentrations for Main Bay during 2005-24 are similar. However, the with-outlet concentrations for East Bay, East Devils Lake, and Stump Lake during that period are much higher than the baseline concentrations. The higher with-outlet concentrations are caused by a combination of two factors--less relatively fresh water from the west part of the lake is available to dilute concentrations in the east part of the lake, and the outlet prevents a natural spill, which releases large amounts of sulfate from Stump Lake to the Sheyenne River. During 2026-50, the maximum with-outlet concentration for each of the lake boxes is higher than the baseline concentration. Thus, water quality in Devils Lake appears to be poorer with an outlet than under natural conditions. However, the inference cannot be made from the wet scenario that a west-end outlet, which removes relatively fresh water, always worsens the water quality in the lake. The processes that affect the water quality are highly complex, and the effect of an outlet is highly dependent on future climatic conditions.

The Corps used the HEC-5Q computer model (U.S Army Corps of Engineers, 1987) to simulate flow and water quality in the Sheyenne River and in the Red River from the confluence with the Sheyenne River to the Canadian border. Results for the wet scenario 450-milligram-per-liter sulfate constraint simulation indicate that the West Bay outlet resulted in significant increases in the frequency of exceedance of water-quality standards over baseline conditions (U.S. Army Corps of Engineers, 2002). For example, for the wet scenario West Bay outlet (alternative A1) 480-cubic-foot-per-second pump capacity simulation with a 450-milligram-per-liter constraint, the Corps' analysis indicated that dissolved solids in the Red River at Halstad, Minn., exceeded 500 milligrams per liter (the standard for dissolved solids in the Red River) about 37 percent of the time during the first 10 years of pumping compared to about 4 percent of the time for baseline conditions. Therefore, outlet alternatives A2, B1, and B2 were developed to lessen the downstream effects of a potential outlet while still maintaining effectiveness for flood control.

Results for the wet scenario modified West Bay outlet (alternative A2) 480-cubic-foot-per-second pump capacity simulation with various sulfate constraints indicate that a 350-milligram-per-liter sulfate constraint reduces the peak lake level nearly as much as a 450-milligram-per-liter sulfate constraint (fig. 37). Reduction of the sulfate constraint from 450 to 350 milligrams per liter results in lower outlet discharges during the first 4 years of pumping but nearly identical outlet discharges during the next 15 years. During the last half of the simulation period, the 350-milligram-per-liter constraint results in much less discharge than the 450-milligram-per-liter constraint. Thus, a much higher secondary peak in lake level occurs during 2040 for the 350-milligram-per-liter constraint. However, the secondary peak still remains well below the primary peak that occurs in 2021.

The modified West Bay outlet 350-milligram-per-liter sulfate constraint simulation (fig. 37) results in essentially the same lake levels as the West Bay outlet 450-milligram-per-liter sulfate constraint simulation (fig. 34). Therefore, the Channel A diversion and Highway 57 mixing barrier results in a significant improvement in the water quality of the outlet discharge while maintaining the same effectiveness for reducing lake levels. However, the Corps' analysis indicated the wet scenario modified West Bay outlet 480-cubic-foot-per-second pump capacity simulation with a 350-milligram-per-liter constraint resulted in a 500-milligram-per-liter dissolved-solids concentration at Halstad being exceeded 27 percent of the time during the first 10 years of pumping. Although 27 percent is a significant improvement from the 37-percent value obtained previously, it is still well above the baseline value of about 4 percent.

The in-lake sulfate concentrations for the wet scenario modified West Bay outlet 480-cubic-foot-per-second pump capacity simulation with a 350-milligram-per-liter sulfate constraint are shown in figure 38. Concentrations in Pelican Lake, West Bay South, and Main Bay are lower with the Channel A diversion and Highway 57 mixing barrier (fig. 38) than without (fig. 36). In particular, the concentrations in West Bay South during the period of high pumping rates (2005-25) are 50 to 100 milligrams per liter lower with the diversion and mixing barrier than without. Conversely, the concentrations in East Bay and East Devils Lake are much higher with the diversion and mixing barrier than without.

Results for the Pelican Lake outlet (alternative B1, not shown) simulation indicate an improvement in water quality from that for the modified West Bay outlet. For a 480-cubic-foot-per-second pump capacity, the sulfate constraint for outlet alternative B1 could be lowered to 300 milligrams per liter while still maintaining about the same outlet discharges as for the modified West Bay outlet 350-milligram-per-liter sulfate constraint simulation. However, the Corps' analysis indicated that the Pelican Lake outlet 480-cubic-foot-per-second pump capacity simulation with a 300-milligram-per-liter constraint resulted in the 500-milligram-per-liter dissolved-solids standard at Halstad being exceeded 17 percent of the time during the first 10 years of pumping. Again, this is an improvement from the 27-percent value obtained for the modified West Bay outlet, but it is still well above the baseline value of about 4 percent. The Pelican Lake outlet 250-milligram-per-liter sulfate constraint simulation with a 300-cubic-foot-per-second pump capacity resulted in about the same reduction in lake levels as the West Bay outlet 450-milligram-per-liter sulfate constraint simulation with a 300-cubic-foot-per-second pump capacity (fig. 33) with minimal effects on downstream water quality. Although the small pump capacity resulted in less flood protection, the alternative was considered promising because the smaller capacity also was less costly than a 480-cubic-foot-per-second pump capacity (U.S. Army Corps of Engineers, 2002).

Results for the wet scenario modified Pelican Lake outlet (alternative B2) 480-cubic-foot-per-second pump capacity simulation with various sulfate constraints indicate that a 250-milligram-per-liter sulfate constraint results in lake levels and outlet discharges that are nearly identical to those for the higher sulfate constraints during the first half of the simulation period (fig. 39). The in-lake sulfate concentrations during 2005-22 (fig. 40) indicate that the concentration in Pelican Lake during that period is about 200 milligrams per liter--well below the 250-milligram-per-liter constraint. Thus,

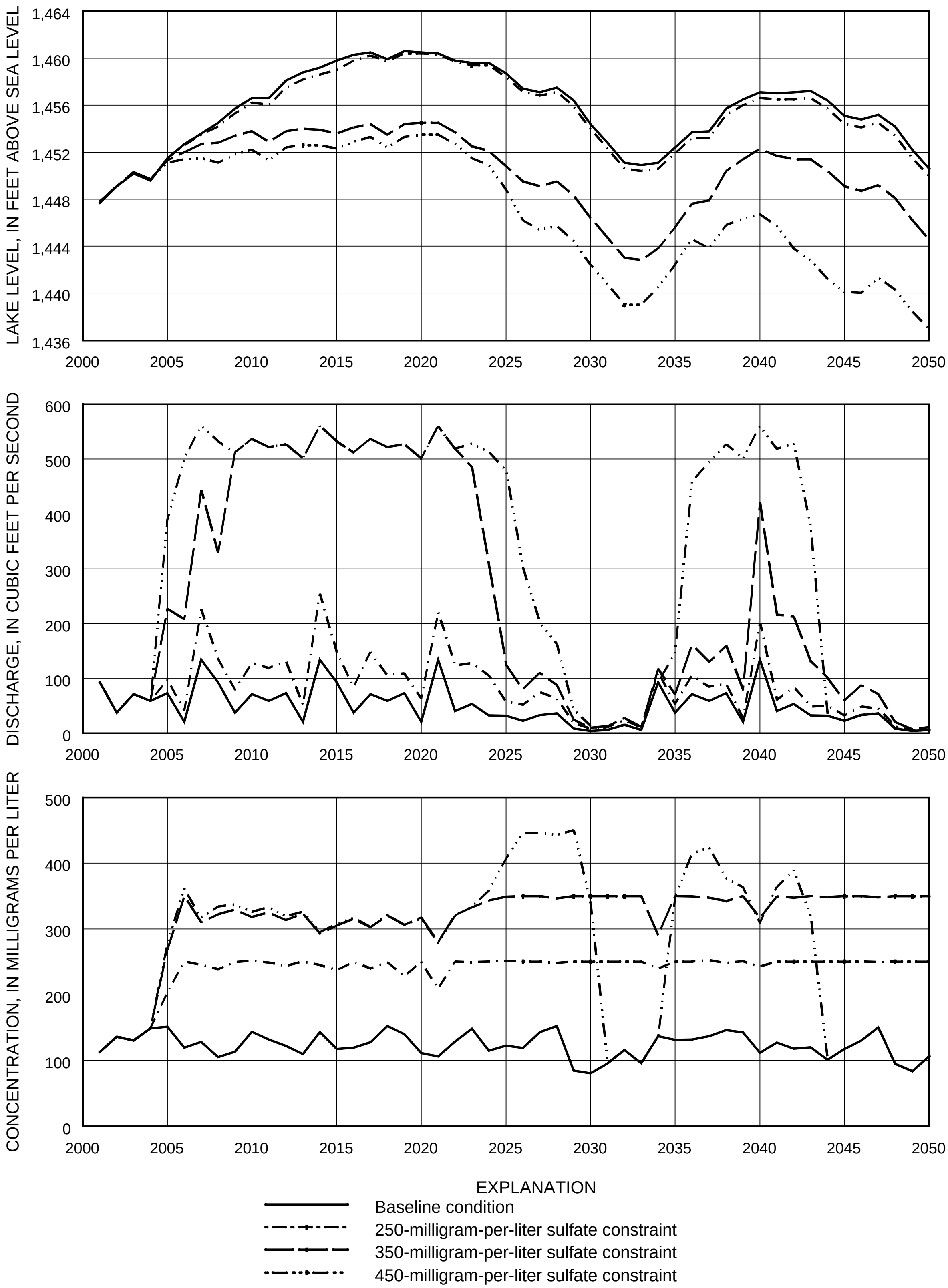

Figure 37. Results for water years 2001-50 for wet scenario modified West Bay outlet 480-cubic-foot-per-second pump capacity simulation. (Top graph indicates annual maximum lake levels of Devils Lake, middle graph indicates average daily discharge for the Sheyenne River below Peterson Coulee, and bottom graph indicates average daily sulfate concentration for the Sheyenne River below Peterson Coulee. Average daily values for the water year are for the pumping window, October through November and May through September.)

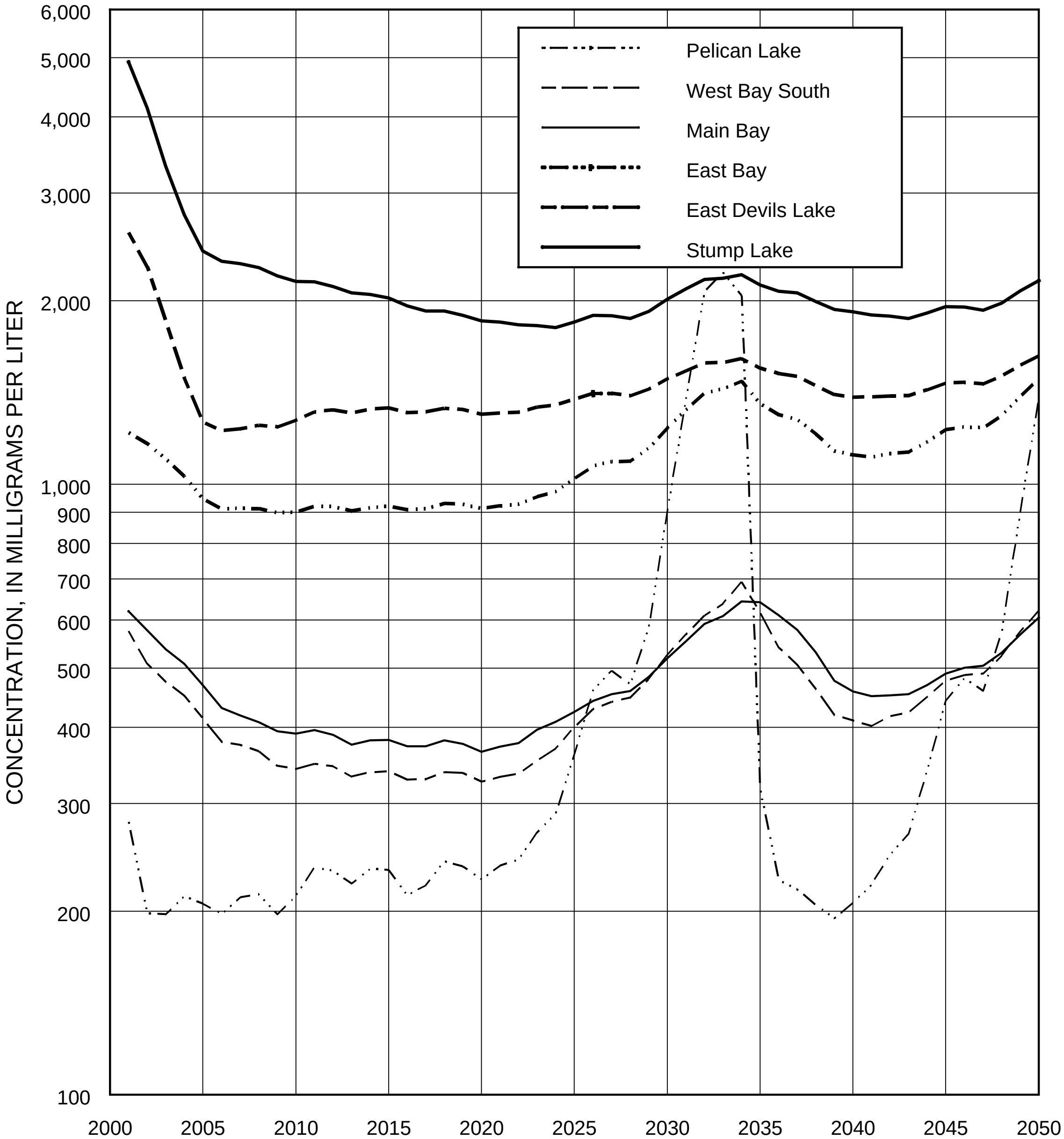

Figure 38. Average annual dissolved sulfate concentrations for Devils Lake for water years 2001-50 for wet scenario modified West Bay outlet 480-cubic-foot-per-second pump capacity simulation with 350-milligram-per-liter sulfate constraint.

the sulfate concentration of the combined ambient Sheyenne River streamflow and outlet discharge (fig. 39) also is well below the 250-milligram-per-liter constraint during that period. The Corps' analysis (U.S. Army Corps of Engineers, 2002) indicated that the wet scenario modified Pelican Lake outlet 480-cubic-foot-per-second pump capacity simulation with a 250-milligram-per-liter constraint resulted in the 500-milligram-per-liter dissolved-solids standard at Halstad being exceeded about 7 percent of the time during the first 10 years of pumping compared to the baseline value of about 4 percent. Overall, the Corps' analysis indicated that the modified Pelican Lake outlet resulted in only minor downstream water-quality changes. Although dissolved-solids concentrations in the Red River increased slightly over baseline concentrations during certain times of the year, concentrations at other times actually decreased as a result of the outlet.

The in-lake sulfate concentrations for the wet scenario modified Pelican Lake outlet (fig. 40) indicate that the concentrations in Pelican Lake tend to be lower than for any of the other outlet alternatives. However, concentrations in West Bay and Main Bay are considerably higher than for any of the other alternatives. The diversion of fresh water from Channel A into Pelican Lake and the discharge of outlet water from Pelican Lake removes as much of the relatively fresh

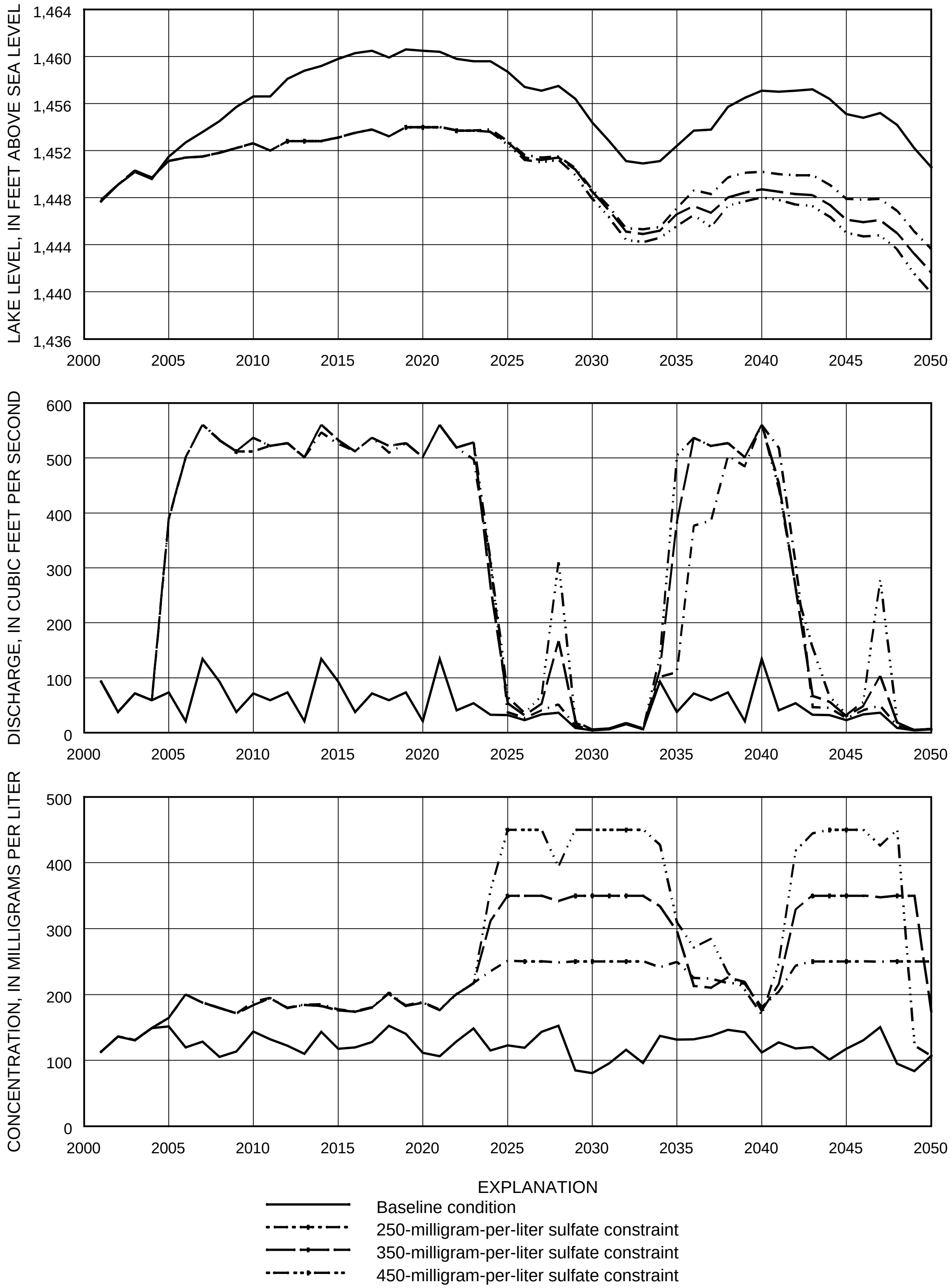

Figure 39. Results for water years 2001-50 for wet scenario modified Pelican Lake outlet 480-cubic-foot-per-second pump capacity simulation. (Top graph indicates annual maximum lake levels of Devils Lake, middle graph indicates average daily discharge for the Sheyenne River below Peterson Coulee, and bottom graph indicates average daily sulfate concentration for the Sheyenne River below Peterson Coulee. Average daily values for the water year are for the pumping window, October through November and May through September.)

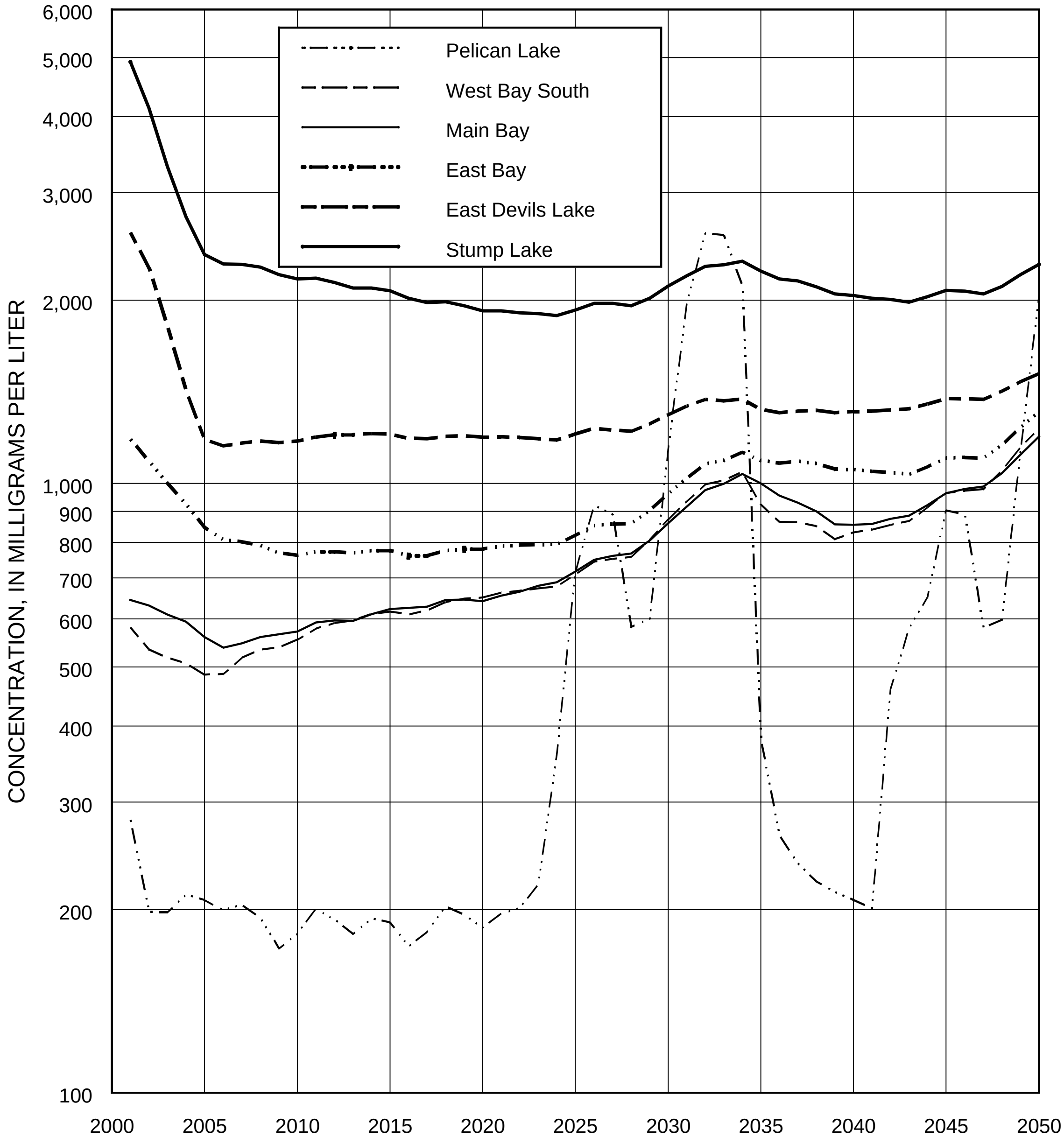

Figure 40. Average annual dissolved sulfate concentrations for Devils Lake for water years 2001-50 for wet scenario modified Pelican Lake outlet 480-cubic-foot-per-second pump capacity simulation with 250-milligram-per-liter sulfate constraint.

water as possible before the water can reach West Bay or Main Bay. Also, the prevention of flow from West Bay to Pelican Lake does not allow for the removal of sulfate from West Bay or Main Bay except for that which escapes to East Bay. Including the Highway 57 mixing barrier with the modified Pelican Lake outlet would reduce sulfate concentrations in West Bay and Main Bay (and increase sulfate concentrations in East Bay and East Devils Lake) but would not substantially change the outlet discharges or the water quality of Pelican Lake.

SIMULATION RESULTS BASED ON STOCHASTIC ANALYSIS

The wet scenario was used to evaluate the effectiveness of various outlet alternatives in terms of controlling rising lake levels under the assumption that precipitation, evaporation, and inflow during the next 2 decades is similar to precipitation, evaporation, and inflow during 1993-99. However, no evaluation was made as to the likelihood that such a scenario might actually occur. Accurate prediction of precipitation or evaporation in the Devils Lake Basin several days, much less several years, in advance is problematic. Because Devils Lake is a large closed lake that responds to long-term climatic conditions, long-term fluctuations in lake levels tend to dominate year-to-year variability (fig. 3). Thus, small changes in average climatic conditions can cause large changes in lake levels on a long-term scale. Furthermore, even if meteorological conditions could be predicted, the amount of runoff still would be uncertain, and uncertainty in predicted runoff would cause uncertainty in predicted volumes of precipitation and evaporation because those volumes depend on the surface area of the lake.

Uncertainty in the amount of runoff, given future meteorological conditions, can be reduced using a detailed watershed model for the Devils Lake Basin. Such a model was developed by WEST Consultants, Inc. (2001), under contract with the Corps, to evaluate the effects of upper basin storage on runoff from the basin. The watershed model can be used to estimate runoff, given initial soil-moisture and surface-storage conditions and future daily precipitation, temperature, and evaporation data, and to evaluate the effects of changes in the upper basin (for example, wetland restoration) on runoff, given future climate scenarios. However, before the watershed model can be used to evaluate probabilities of future lake levels, a stochastic model needs to be developed to generate the future climatic inputs for a large grid of locations in the basin, and the watershed model needs to be run thousands of times with different generated sequences of inputs. This approach was too computationally intensive for purposes of this study, and development and verification of a stochastic model to generate climatic inputs at such detailed temporal and spatial resolution is beyond the scope of this study. Therefore, for this study, a relatively simple time-series model was developed to generate monthly inputs to the water mass-balance model described previously.

Time-Series Model Used to Generate Monthly Water-Balance Data

The time-series model developed for this study is a particular type of multivariate autoregressive model in which input values for a given month depend on antecedent input values plus random noise. The model is similar to a model described by Wiche and Vecchia (1996) to generate quarterly precipitation, evaporation, and inflow data for Devils Lake.

The input values required for the water mass-balance equations (eqs. 4 through 9) include monthly values of precipitation (P), evaporation (E), inflow from Big Coulee (Q_B), and inflow from Channel A (Q_A). The remaining terms in equations 4 through 9 were calculated numerically as described in appendix A. To simplify the time-series model, inflow from Big Coulee and Channel A was combined into total gaged inflow $(G = Q_A + Q_B)$. The procedure for disaggregating total gaged inflow into inflow from Big Coulee and Channel A is described in a later section. To further simplify the time-series model, monthly values for October through March were combined into values for a single winter season. The procedure for disaggregating values for the winter season into values for each month also is described in a later section.

The time-series model was calibrated using estimated monthly precipitation, evaporation, and inflow values for 1980-99 (see equation 3 and figure 12 and the related discussion). The fitted time-series model is given in table 10, and the procedures used to calibrate and verify the model are described in this section.

Each variable (P, E, and G) in the model was transformed using power transformations to remove skewness and seasonality. The particular form of the power transformation for each variable was selected, using methods described by Box and Cox (1964), to make the distribution of the model residuals for the transformed variables as close as possible to a standard normal distribution.

The methods described by Wiche and Vecchia (1996) were used to determine the best combination of antecedent values of the transformed variables to use in the time-series model equations for each season. The time-series model depends on the order in which the variables are included. The best fit was obtained by including evaporation, then precipitation, and then gaged inflow. For example, to predict transformed evaporation for the winter season $(EWIN)$, antecedent values of transformed evaporation were considered as explanatory variables. Because evaporation is the first variable in the model, antecedent values of transformed precipitation and gaged inflow were not considered. The antecedent values of transformed evaporation contained no significant predictors of $EWIN$.

To predict transformed precipitation for the winter season $(PWIN)$, antecedent values of transformed evaporation and precipitation and the concurrent value of $EWIN$ were considered as explanatory variables. The best explanatory variable

Table 10. Fitted time-series model used to generate monthly water mass-balance model inputs based on monthly precipitation, evaporation, and inflow values for 1980-99

Season	Transformed variable[1]	Equation to generate transformed variable for jth water year[2]	Coefficient of determination (percent)
$WIN(OCT-MAR)$	$EWIN = (E-4.13)/1.53$	$EWIN(j) = Z$	0
	$PWIN = (P^{1/3}-1.78)/0.23$	$PWIN(j) = -0.68EWIN(j)+0.61Z$	56
	$GWIN = (G^{1/4}-7.73)/3.83$	$GWIN(j) = 0.85GSEP(j-1)+0.39PWIN(j)+0.48Z$	80
APR	$EAPR = (E-1.27)/0.66$	$EAPR(j) = Z$	0
	$PAPR = (P^{1/3}-1.01)/0.30$	$PAPR(j) = Z$	0
	$GAPR = (G^{1/4}-10.75)/5.36$	$GAPR(j) = 0.70GWIN(j)+0.40PWIN(j)+0.42Z$	84
MAY	$EMAY = (E-3.68)/0.46$	$EMAY(j) = 0.50EAPR(j)+0.87Z$	25
	$PMAY = (P^{1/3}-1.26)/0.23$	$PMAY(j) = Z$	0
	$GMAY = (G^{1/4}-10.1)/5.87$	$GMAY(j) = 0.94GAPR(j)+0.22[PAPR(j)-EAPR(j)]+0.24Z$	91
JUN	$EJUN = (\log E-0.22)/0.26$	$EJUN(j) = 0.28EMAY(j)+0.97Z$	8
	$PJUN = (P^{1/3}-1.58)/0.22$	$PJUN(j) = -0.43EJUN(j)+0.92Z$	19
	$GJUN = (G^{1/4}-8.07)/4.79$	$GJUN(j) = 0.98GMAY(j)+0.08[PJUN(j)-EJUN(j)]+0.20Z$	96
JUL	$EJUL = (E-5.48)/0.94$	$EJUL(j) = 0.43EMAY(j)+0.84Z$	29
	$PJUL = (P^{1/3}-1.52)/0.35$	$PJUL(j) = -0.63EJUL(j)+0.83Z$	34
	$GJUL = (G^{1/4}-6.73)/4.62$	$GJUL(j) = 0.84GJUN(j)+0.13[PJUL(j)-EJUL(j)]+0.28Z$	92
AUG	$EAUG = (E-6.03)/0.62$	$EAUG(j) = 0.82EJUL(j)+0.61Z$	63
	$PAUG = (P^{1/3}-1.35)/0.25$	$PAUG(j) = Z$	0
	$GAUG = (G^{1/4}-6.1)/4.74$	$GAUG(j) = 0.85GJUL(j)+0.16[PAUG(j)-EAUG(j)]+0.39Z$	86
SEP	$ESEP = (E-4.82)/0.63$	$ESEP(j) = 0.44EAUG(j)+0.83Z$	31
	$PSEP = (P^{1/3}-1.22)/0.27$	$PSEP(j) = 0.47PAUG(j)+0.86Z$	23
	$GSEP = (G^{1/4}-5.27)/4.01$	$GSEP(j) = 0.95GAUG(j)+0.33Z$	90

[1] E is evaporation, in inches, for the given season; P is precipitation, in inches, for the given season; and G is gaged inflow (inflow from Big Coulee and Channel A), in acre-feet, for the given season.

[2] Z is a standard normal random variable that is generated independently for each seaon and each transformed variable.

was the concurrent value of $EWIN$. The estimated multiplier (-0.68) was highly significant (p-value less than 0.01), and the coefficient of determination was 56 percent. Thus, high winter evaporation tends to be accompanied by low winter precipitation, and low winter evaporation tends to be accompanied by high winter precipitation. Other explanatory variables were not significant predictors of $PWIN$ (given that the concurrent value of $EWIN$ already was in the model).

To predict transformed gaged inflow for the winter season $(GWIN)$, concurrent and antecedent values of transformed evaporation, concurrent and antecedent values of transformed precipitation, and antecedent values of transformed inflow were considered as explanatory variables. The best combination of explanatory variables was transformed inflow from the previous September $(GSEP)$ and the concurrent value of $PWIN$. The estimated multipliers for $GSEP$ (0.85) and $PWIN$ (0.39) were highly significant, and the coefficient of determination was 80 percent. Thus, high September inflow and high winter precipitation tend to produce high winter inflow.

The time-series model equations for the remaining seasons were obtained using a procedure similar to that for the winter season. Most of the explanatory variables and estimated multipliers given in table 10 appear reasonable. For example, the estimated multipliers that relate transformed evaporation in each season to antecedent values of transformed evaporation are positive and indicate a moderate degree of serial persistence in evaporation. The strongest relation occurs between August evaporation $(EAUG)$ and the previous July evaporation $(EJUL)$, with a multiplier of 0.82. However, transformed evaporation in winter $(EWIN)$ and April $(EAPR)$ are not related to antecedent values of transformed evaporation.

The relations between transformed precipitation in each season and antecedent values of transformed precipitation were not significant except in September when a moderate degree of dependence was shown between September precipitation $(PSEP)$ and August precipitation $(PAUG)$. The multipliers that relate $PWIN$, June precipitation $(PJUN)$, and July precipitation $(PJUL)$ to concurrent values of transformed evaporation are all negative, indicating high precipitation in those seasons tends to be accompanied by low evaporation.

The equations given in table 10 for gaged inflow also are reasonable. The estimated multipliers that relate transformed inflow in each season to antecedent values of transformed inflow and to $PWIN$ indicate a high degree of serial persistence in inflow that probably is caused by storage of water in the Devils Lake Basin in the form of soil moisture, surface-water bodies, and snowpack. High inflow in September usually is indicative of high soil-moisture and surface-water storage in the basin at the beginning of winter freezeup and tends to result in more of the following winter and spring precipitation entering the lake in the form of inflow. Thus, a combination of high $GSEP$ and high $PWIN$ tends to produce high inflows during the following year. Because of the flat topography of the basin and the relatively slow spring thaw, runoff from a high winter snowpack may take months to subside. Thus, the persistence in inflows remains well into the summer and fall as indicated by the high positive multipliers that relate transformed inflow in each season to antecedent values of transformed inflow. A significant positive relation also occurs between April inflow $(GAPR)$ and $PWIN$ and between May inflow $(GMAY)$ and April precipitation minus evaporation $(PAPR - EAPR)$, indicating a combination of high precipitation in the winter and high net precipitation (transformed precipitation minus transformed evaporation) in April tends to increase inflows in April and May. High net precipitation in June, July, and August also tends to increase inflows during those months as indicated by the positive multipliers that relate transformed inflows during those months to concurrent values of transformed precipitation minus transformed evaporation.

Recorded and fitted values of the transformed variables for 1980-99 are shown in figure 41 (the fitted value for a particular variable was obtained by setting Z equal to zero). All of the seasons were combined into a single plot for each variable although the degree of linear dependence differs among the seasons as indicated by the differences in the coefficients of determination. The best relation between the recorded and fitted values occurs for inflow. The coefficient of determination for inflow ranges from 80 percent in the winter to 96 percent in June. The relations between recorded and fitted values for evaporation and precipitation are similar, and both relations are much weaker than the relation for inflow. The coefficient of determination for evaporation ranges from zero in the winter and April to 63 percent in August and averages about 23 percent for all seasons. The coefficient of determination for precipitation ranges from zero in several seasons to 56 percent in the winter and averages about 19 percent for all seasons.

Because the fitted time-series model, including the random noise, Z, will be used to generate inputs to the water mass-balance model, a probability distribution was assumed for the noise. As indicated earlier, the power transformations were selected to make the noise as close as possible to a standard normal distribution. Normal probability plots of the time-series model residuals (the recorded values minus the fitted values, divided by the multiplier for Z) (fig. 42) indicate the residuals for evaporation and precipitation closely approximate a normal distribution. However, the residuals for inflow appear to deviate from the normal distribution for values less than -1 and greater than +1. The deviation for values less than -1 is caused by the actual transformed inflows being bounded below, whereas a normal distribution is not bounded below. For example, the smallest value that transformed August inflow $(GAUG)$ can attain (table 10) is -1.28 (-6.1/4.74) when G = 0. Therefore, whenever the time-series model generates a value for $GAUG$ that is less than -1.28, the value is set equal to -1.28, effectively truncating the lower tail of the distribution and producing a generated inflow of zero. Inflows of zero also can be generated for other months, but the chances of precipitation or evaporation being zero (other than for April) are extremely small. The deviation for values greater than +1 was not significant.

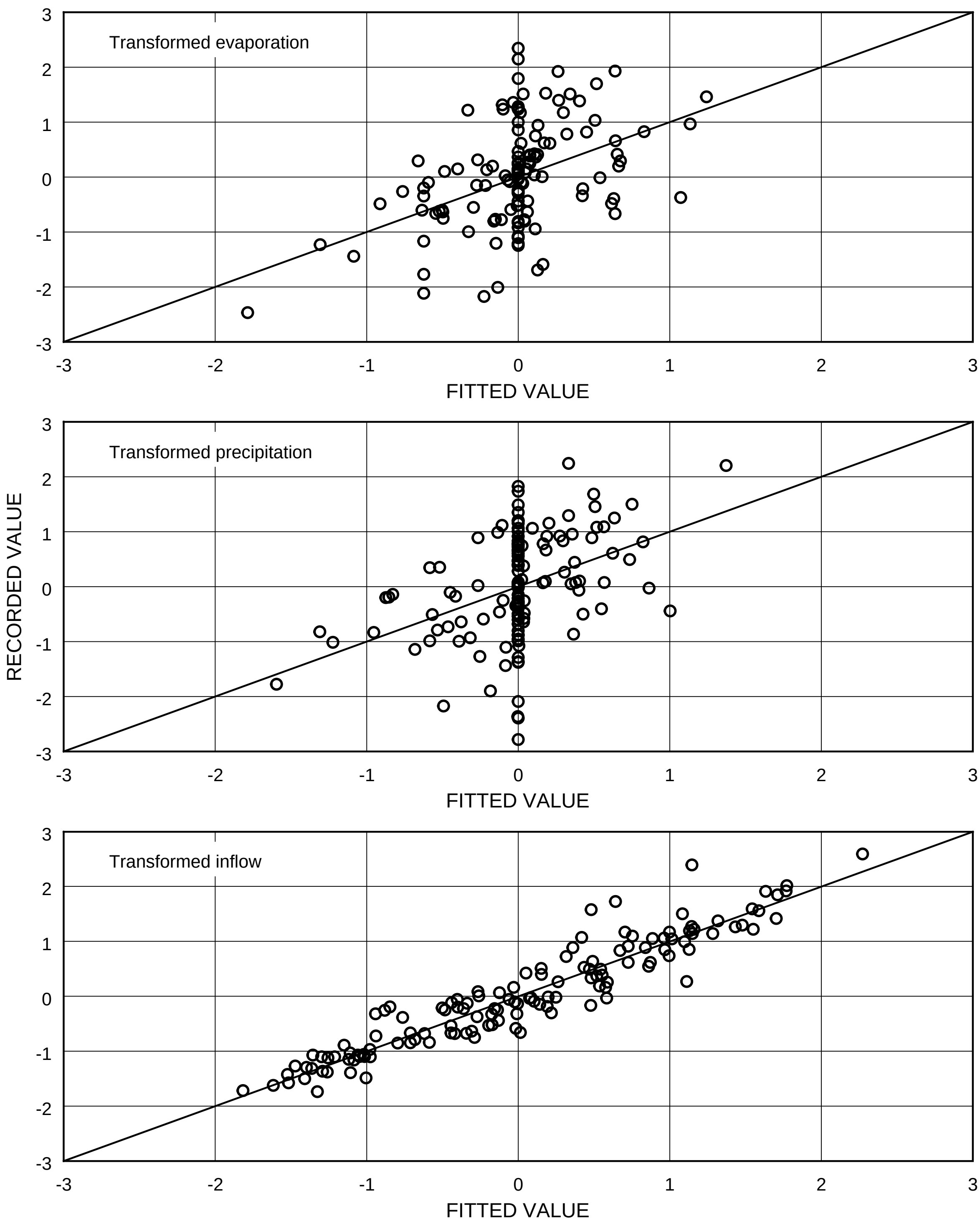

Figure 41. Recorded and fitted values of transformed evaporation, precipitation, and gaged inflow for 1980-99. (Circles indicate recorded values, and lines indicate fitted values.)

Time-Series Model Verification Using Long-Term Recorded Data

Previous discussion indicates that the time-series model provides a good representation of the joint variation of the input values for the 1980-99 calibration period. However, because of the nonstationarity of precipitation (see table 1 and figure 4 and the related discussion), the time-series model cannot be expected to provide a good representation of the long-term historical variability of the input values without minor modifications.

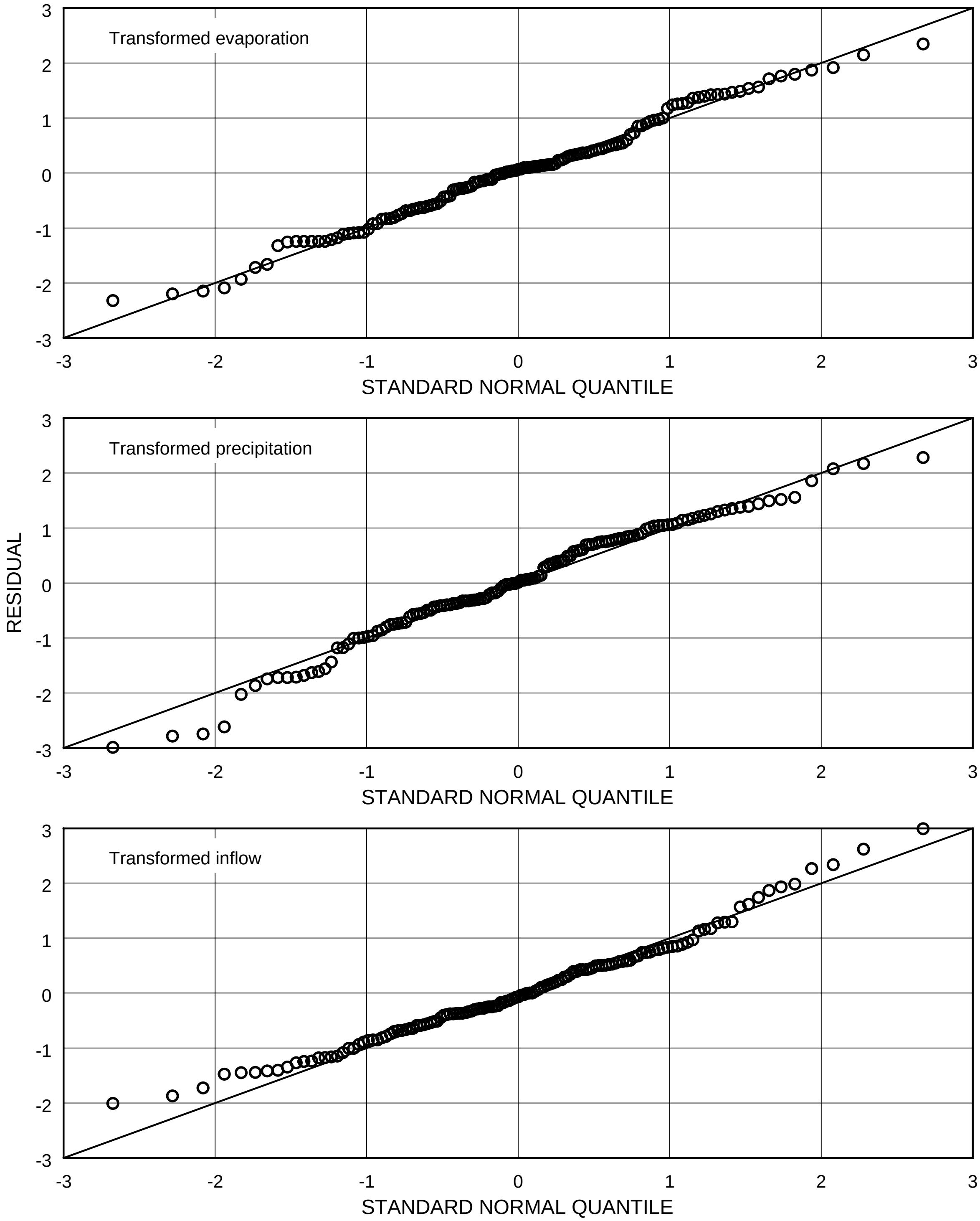

Figure 42. Normal probability plots of residuals for transformed evaporation, precipitation, and gaged inflow for 1980-99.

Perhaps the most important requirement of the time-series model from a long-term perspective is that the model can accurately represent changes in inflow caused by changes in precipitation or evaporation. To verify that the model satisfies this requirement, monthly precipitation, evaporation, and inflow data for 1950-78 were used as a cross-validation data set. The precipitation data were from the NWS gage at Devils Lake, the evaporation data were from Wiche and Vecchia (1996), and the gaged inflow data were from Big Coulee. Inflow data from before 1950 are not available because no streamflow gage existed on Big Coulee before that time, and data for 1979 were not used because that was the first year of operation of Channel A and daily streamflow data are unavailable for Channel A. Indirect estimation of monthly streamflow for Channel A in 1979 also was difficult because of insufficient data.

To obtain adjusted precipitation and evaporation values for the model, the monthly precipitation and evaporation data for 1950-78 were multiplied by the estimated coefficients given in table 2. The adjusted values and the recorded values of inflow for 1950-78 then were transformed using the transformations given in table 10, and the fitted values and residuals for gaged inflow (figs. 43 and 44, bottom plots) were computed using the time-series model equations given in table 10.

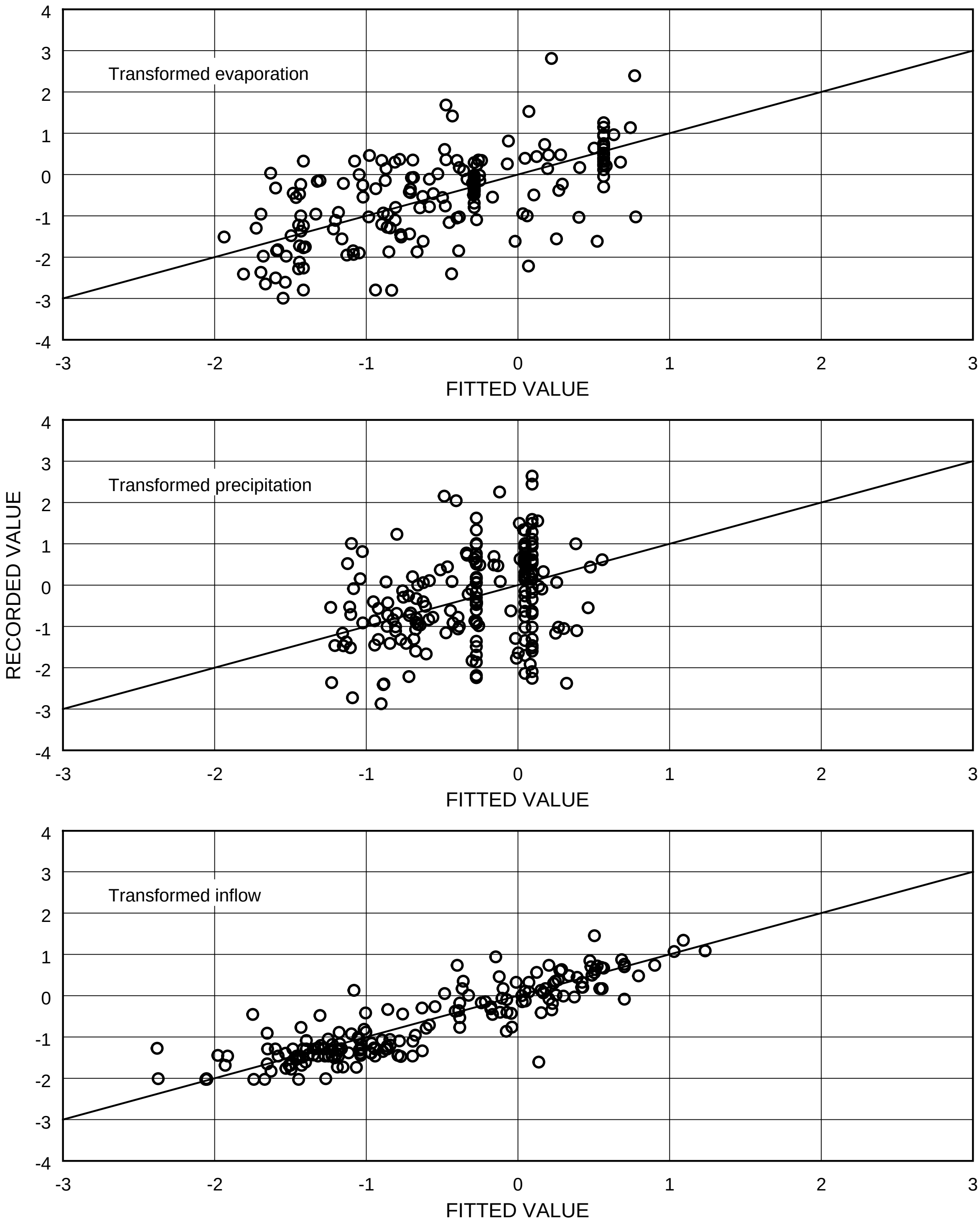

Figure 43. Recorded and fitted values of transformed evaporation, precipitation, and gaged inflow for 1950-78. (Circles indicate recorded values, and lines indicate fitted values.)

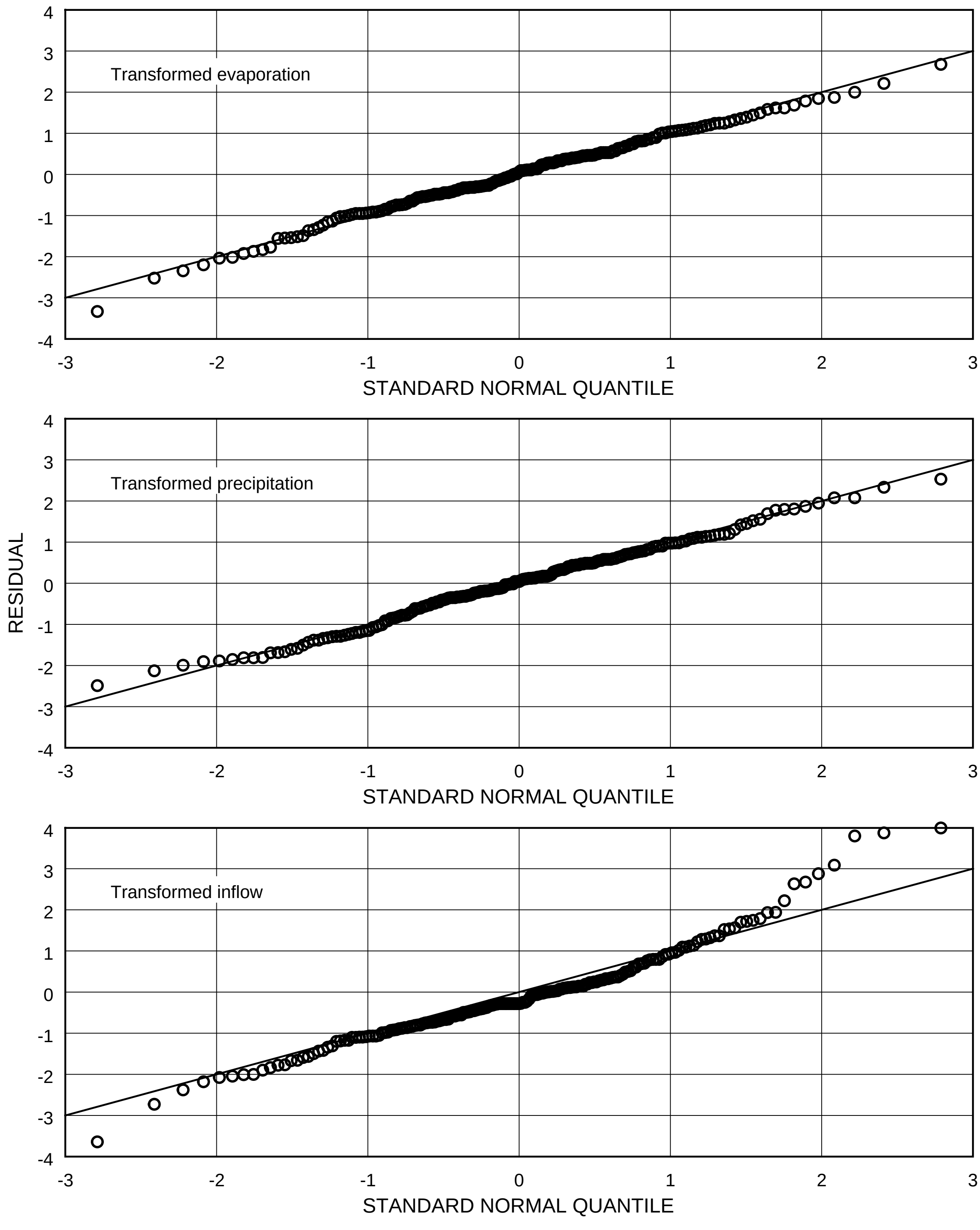

Figure 44. Normal probability plots of residuals for transformed evaporation, precipitation, and gaged inflow for 1950-78.

A good relation exists between the recorded and fitted values of inflow for 1950-78 (fig. 43). Thus, the simple time-series model for gaged inflow given in table 10 (conditioned on precipitation and evaporation) seems to adequately represent the changes in inflow caused by the changes in climatic conditions. As shown in figures 41 and 43, the generally drier conditions during 1950-78 resulted in a much higher frequency of low inflows and a much lower frequency of high inflows than the generally wetter conditions during 1980-99.

The time-series model seems to work equally well for generatiang inflow for both the calibration and cross-validation data. For both data sets, the points (figs. 41 and 43, bottom plots) fall along the line of equality between the recorded and fitted values, and the variability of the points around the line of equality (figs. 42 and 44, bottom plots) is similar. The cross-validation residuals (fig. 44) closely approximate a standard normal distribution except for a few high residuals. The tendency for the high residuals to deviate from the normal distribution also is indicated in the calibration residuals (fig. 42) although to a much lesser extent. To determine the cause of the high residuals and to determine if they could signify a serious problem with the model, the cross-validation residuals were examined in more detail. The unusually high residuals all occurred during June or July and corresponded with years in which a dry fall and winter (October through March) was followed by a very wet spring (April through June). For example, the two highest cross-validation residuals occurred during June and July 1954. During that year, only 3.78 inches of precipitation fell during October through March, and 13.1 inches of precipitation fell during April through June. Gaged inflow during April and May of that year was zero, but gaged inflow during June was about 4,000 acre-feet and gaged inflow during July was about 17,000 acre-feet. The time-series model predicted essentially no inflow in June and about 1,700 acre-feet of inflow in July. Because the cross-validation data set had more years with dry winters and wet springs than the calibration data set, the high residuals were more evident in the cross-validation data. However, because the high residuals occurred during years that had relatively low inflows and because of the low frequency of occurrence of the high residuals, the residuals were not indicative of a serious problem in using the model to simulate gaged inflow. As indicated later using model verification runs, the time-series model given in table 10 adequately simulates inflows for both the calibration and cross-validation periods.

The model given in table 10 does not, however, adequately account for nonstationarity in precipitation or evaporation. As indicated by the model equations given in table 10, the statistical properties of transformed evaporation and precipitation depend only on the statistical properties of the noise (Z) and on the model coefficients. For example, $EWIN$ depends only on the concurrent value of Z for $EWIN$, and $PWIN$ depends only on the concurrent value of Z for $EWIN$ (multiplied by -0.68) and the concurrent value of Z for $PWIN$ (multiplied by 0.61). A sequential application of the equations for transformed evaporation and precipitation in the remaining seasons indicates transformed evaporation and precipitation in any given year depend only on the values of Z for that year multiplied by certain constants that depend on the fitted model. Therefore, the statistical properties of evaporation and precipitation can be modified only by modifying the statistical properties of Z and/or modifying the fitted model equations.

The model equations for transformed evaporation and precipitation could be slightly modified to reproduce the statistical properties of the variables for the cross-validation data set. For the modification, the noise for each season and each variable was assumed to be a normal random variable with a seasonally varying mean rather than a normal random variable with a mean of zero. The modified equations to generate transformed evaporation and precipitation for the cross-validation data set are given in table 11. For the calibration data, $EWIN$ was normally distributed with a mean of zero and a standard deviation of 1. However, for the cross-validation data, $EWIN$ was normally distributed with a mean of -0.29 and a standard deviation of 0.22 (the multiplier for Z). Therefore, winter evaporation was lower and less variable for the cross-validation data than for the calibration data. For the calibration data, $PWIN + 0.68EWIN$ (the recorded value minus the fitted value) was approximately normally distributed with a mean of zero and a standard deviation of 0.61. However, for the cross-validation data, $PWIN + 0.68EWIN$ was approximately normally distributed with a mean of -0.93 and a standard deviation of 0.80. Using conditioning arguments, the mean of $PWIN$ is zero for the calibration data and -1.13 for the cross-validation data, and the standard deviation of $PWIN$ is 0.91 for the calibration data and 0.81 for the cross-validation data. Therefore, winter precipitation was lower and less variable for the cross-validation data than for the calibration data.

The modified time-series model yields a relation between recorded and fitted values of transformed evaporation and precipitation for the cross-validation data (fig. 43) that is similar to the relation for the calibration data (fig. 41). Evaporation for the cross-validation data tends to be lower than evaporation for the calibration data, and precipitation for the cross-validation data tends to be lower and less variable than precipitation for the calibration data. The time-series model residuals for evaporation and precipitation for the cross-validation data (fig. 44) closely approximate a standard normal distribution.

To further validate the time-series models for the calibration and cross-validation periods, the fitted models given in tables 10 and 11 were used to generate 200 independent sequences of transformed evaporation, precipitation, and inflow data for each period. The generated data then were untransformed and compared to the recorded data for the respective period. Each of the 200 generated sequences was the same length as the respective historical period (20 years for the

Table 11. Modifications to fitted time-series model used to generate monthly water mass-balance model inputs based on monthly precipitation, evaporation, and inflow values for 1950-78

[Transformed variables are defined in table 10]

Season	Transformed variable	Equation to generate transformed variable for jth water year based on calibration data (1980-99)	Equation to generate transformed variable for jth water year based on cross-validation data (1950-78)
$WIN(OCT - MAR)$	$EWIN$	$EWIN(j) = Z$	$EWIN(j) = -0.29 + 0.22Z$
	$PWIN$	$PWIN(j) = -0.68EWIN(j) + 0.61Z$	$PWIN(j) = -0.68EWIN(j) - 0.93 + 0.80Z$
APR	$EAPR$	$EAPR(j) = Z$	$EAPR(j) = 0.57 + 0.34Z$
	$PAPR$	$PAPR(j) = Z$	$PAPR(j) = 0.05 + 0.88Z$
MAY	$EMAY$	$EMAY(j) = 0.50EAPR(j) + 0.87Z$	$EMAY(j) = 0.50EAPR(j) - 1.79 + 0.93Z$
	$PMAY$	$PMAY(j) = Z$	$PMAY(j) = 0.09 + 1.30Z$
JUN	$EJUN$	$EJUN(j) = 0.28EMAY(j) + 0.97Z$	$EJUN(j) = 0.28EMAY(j) - 0.34 + 0.97Z$
	$PJUN$	$PJUN(j) = -0.43EJUN(j) + 0.92Z$	$PJUN(j) = -0.43EJUN(j) - 0.95 + 1.18Z$
JUL	$EJUL$	$EJUL(j) = 0.43EMAY(j) + 0.84Z$	$EJUL(j) = 0.43EMAY(j) + 0.27 + 0.68Z$
	$PJUL$	$PJUL(j) = -0.63EJUL(j) + 0.83Z$	$PJUL(j) = -0.63EJUL(j) - 0.93 + 0.70Z$
AUG	$EAUG$	$EAUG(j) = 0.82EJUL(j) + 0.61Z$	$EAUG(j) = 0.82EJUL(j) + 0.39 + 1.17Z$
	$PAUG$	$PAUG(j) = Z$	$PAUG(j) = -0.27 + 1.06Z$
SEP	$ESEP$	$ESEP(j) = 0.44EAUG(j) + 0.83Z$	$ESEP(j) = 0.44EAUG(j) - 0.98 + 0.90Z$
	$PSEP$	$PSEP(j) = 0.47PAUG(j) + 0.86Z$	$PSEP(j) = 0.47PAUG(j) + 0.12 + 1.27Z$

calibration period and 29 years for the cross-validation period). However, each of the sequences was not expected to exactly reproduce the statistics of the recorded data because the recorded data were just one possible realization that occurred. For example, even if the climatic conditions during the next 20 years are the same as those that occurred during 1980-99, a particular statistic, such as average annual inflow, computed for the next 20 years should not be expected to be exactly the same as the corresponding statistic for 1980-99. However, if the time-series model consistently generates values of a particular statistic that are either higher or lower than the recorded values, the time-series model is not consistent with the recorded data and the validity of the model should be questioned. The validity of the time-series model also should be questioned if the model produces physically unrealistic values of a particular statistic (for example, 10 inches of average annual evaporation and 50 inches of average annual precipitation are unrealistic values for those statistics for the Devils Lake Basin).

Selected statistics of the recorded and generated data for the calibration period are given in table 12. The generated values for annual evaporation, precipitation, and gaged inflow are consistent with the recorded values except possibly for maximum annual evaporation. Although the recorded maximum value for evaporation (38.1 inches) is within the range of generated values (34.4 to 38.7 inches), most of the generated values were less than the recorded value. The recorded average value for precipitation was 22.7 inches, and the mean of the generated values was 22.4 inches. Of the generated values, 80 percent were between 21.1 and 23.8 inches (10 percent were less than 21.1 inches, and 10 percent were greater than 23.8 inches). Thus, the generated values were neither consistently greater than nor less than the recorded value, and the range of the generated values is reasonable. The recorded minimum and maximum values for precipitation are well within the range of generated values, and the recorded average value for inflow (115,200 acre-feet), which is the most important statistic from a water-balance perspective, is well within the range of generated values (50,200 to 190,400 acre-feet). Although a high degree of variability exists in the generated values for inflow, as indicated by the large range of values, such variability is reasonable. For example, if the 1987-91 drought had not occurred, the average annual inflow during 1980-99 easily could have been much higher than the recorded value, and if the drought had been longer, the average annual inflow could have been much less than the recorded value.

Table 12. Statistics of recorded and generated annual (October through September) evaporation, precipitation, and inflow data for 1980-99

Variable	Statistic	Recorded value	Mean of generated values[1]	Range of generated values[2]
Annual evaporation, in inches	Average	30.9	30.8	30.0 to 31.6
	Minimum	25.7	25.8	24.0 to 27.4
	Maximum	38.1	36.4	34.4 to 38.7
Annual precipitation, in inches	Average	22.7	22.4	21.1 to 23.8
	Minimum	14.6	14.6	12.5 to 16.8
	Maximum	31.3	33.2	28.7 to 38.7
Annual gaged inflow, in acre-feet	Average	115,200	109,700	50,200 to 190,400
	Minimum	40	1,200	0 to 3,300
	Maximum	488,800	595,300	222,600 to 1,129,100

[1]Mean of the generated values of the given statistic for 200 generated 20-year sequences.

[2]Range containing 80 percent of the generated values of the given statistic for 200 generated 20-year sequences.

The recorded minimum value for inflow for 1980-99 was only 40 acre-feet, and the range of generated values for that statistic was zero to 3,300 acre-feet (table 12). Thus, even during wet climatic conditions similar to those during 1980-99, the probability for essentially no inflow sometime in a 20-year period is high. Conversely, the probability of a very high inflow sometime in a 20-year period is moderate as indicated by the large range of generated values for maximum annual inflow. Of the generated values, 10 percent exceeded 1,129,100 acre-feet, which is more than twice the historical inflow that occurred in 1997 (488,800 acre-feet). Such a high inflow easily could occur given a winter snowpack similar to that in 1997 and a wet spring and summer similar to those in 1999.

Selected statistics of the recorded and generated data for the cross-validation period are shown in table 13. The recorded values for evaporation, precipitation, and gaged inflow are well within the range of generated values except for minimum annual evaporation and maximum annual precipitation. Most of the generated values for minimum annual evaporation were less than the recorded value, and most of the generated values for maximum annual precipitation were greater than the recorded value. However, the ranges of the generated values for those statistics are reasonable and include the recorded values.

Table 13. Statistics of recorded and generated annual (October through September) evaporation, precipitation, and inflow data for 1950-78

Variable	Statistic	Recorded value	Mean of generated values[1]	Range of generated values[2]
Annual evaporation, in inches	Average	28.4	28.5	27.9 to 29.0
	Minimum	25.9	24.3	23.2 to 25.8
	Maximum	33.6	32.8	31.3 to 34.3
Annual precipitation, in inches	Average	18.3	18.4	17.3 to 19.5
	Minimum	9.8	10.9	9.1 to 12.5
	Maximum	25.3	29.7	25.1 to 34.7
Annual gaged inflow, in acre-feet	Average	27,000	21,700	7,100 to 38,100
	Minimum	0	0	0 to 0
	Maximum	152,200	190,800	57,800 to 339,700

[1]Mean of the generated values of the given statistic for 200 generated 29-year sequences.

[2]Range containing 80 percent of the generated values of the given statistic for 200 generated 29-year sequences.

For many of the statistics (tables 12 and 13), the ranges of generated values for the two periods do not overlap. For example, 90 percent of the generated values for average precipitation for 1980-99 were greater than 21.1 inches, but 90 percent of the generated values for 1950-78 were less than 19.5 inches. In addition, 90 percent of the generated values for average inflow for 1980-99 were greater than 50,200 acre-feet, but 90 percent of the generated values for 1950-78 were less than 38,100 acre-feet. The extremely wide disparity between the two historical periods reaffirms the results given in table 1 that indicate the calibration and cross-validation periods cannot be assumed to be part of a stationary climatic regime.

Time-Series Model Verification Using Geologic History of Lake-Level Fluctuations

The time-series models given in tables 10 and 11 provided a good representation of historical variability in recorded evaporation, precipitation, and inflow for the relatively recent past (1950-99), but the models also need to represent historical variability on a much longer time scale to be used to calculate probabilities for the outlet simulation model. To verify that the models could be used to reproduce the geologic history of lake-level fluctuations for Devils Lake, the time-series models were used to generate 5,000 years of monthly inputs, which were, in turn, used in the Devils Lake water mass-balance equations (eqs. 4 through 9) to generate 5,000 years of monthly lake levels for Devils Lake for the two climatic periods (1980-99 and 1950-78). The generated lake levels then were evaluated in relation to the geologic history of lake-level fluctuations of Devils Lake developed by the North Dakota Geological Survey (Bluemle, 1991; Murphy and others, 1997).

To generate the 5,000 years of monthly inputs, generated transformed values of evaporation, precipitation, and inflow were untransformed to obtain generated seasonal values. The values for the winter season then were multiplied by the ratios given in table 14 to disaggregate the seasonal values into monthly values, and the monthly values of gaged inflow

Table 14. Average ratios of monthly water-balance inputs to winter water-balance inputs for water years 1980-99

Month	Ratio for evaporation	Ratio for precipitation	Ratio for gaged inflow
October	0.69	0.28	0.08
November	.31	.16	.10
December	0	.12	.06
January	0	.13	.04
February	0	.11	.06
March	0	.20	.66

were multiplied by the ratios given in table 15 to obtain monthly values of inflow from Big Coulee and Channel A. The ratios given in tables 14 and 15 are average values for water years 1980-99. The actual ratios vary from year to year, but the generated values assume the same ratios year after year.

Generated monthly values for evaporation, precipitation, inflow from Big Coulee, and inflow from Channel A were used as inputs to the water mass-balance equations (eqs. 4 through 9) to generate monthly lake levels for Devils Lake and to compute monthly volumes of the lake boxes for both 5,000-year sequences. Starting volumes at the beginning of the simulation period were the actual volumes of the lake boxes on September 30, 2000. The starting volumes are important for deriving conditional lake-level probabilities in a later section of this report. In the conditional lake-level probability analysis, each of the conditional lake-level simulations will begin on October 1, 2000. Therefore, the starting volumes (and the starting values for $GSEP$) for the 5,000-year sequences were the same as those used for the conditional lake-level probability analysis. Long-term frequency analysis based on the 5,000-year sequences is not sensitive to the assumed starting values because the effect of the starting values becomes negligible after the first 100 years of the simulation period.

Table 15. Average ratios of monthly inflow from Big Coulee and monthly inflow from Channel A to gaged inflow for water years 1980-99

Month	Ratio for Big Coulee	Ratio for Channel A
October	0.40	0.60
November	.35	.65
December	.67	.33
January	.96	.04
February	.91	.09
March	.54	.46
April	.52	.48
May	.59	.41
June	.75	.25
July	.77	.23
August	.51	.49
September	.57	.43

Generated 20-year average annual evaporation and precipitation data for the two climatic periods (1980-99 and 1950-78) are shown in figure 45. Generated monthly values were summed to obtain annual values, and the annual values were averaged over a 20-year moving window to smooth some of the noise in the generated data. The climate during 1980-99 is referred to as the "wet" climate, and the climate during 1950-78 is referred to as the "normal" climate. For the wet climate, the mean of the evaporation data shown in figure 45 is 30.8 inches, and the mean of the precipitation data is 22.4 inches. For the normal climate, the mean of the evaporation data is 28.5 inches, and the mean of the precipitation data is 18.4 inches. The variability of the evaporation and precipitation data around their long-term means is higher for the wet climate than for the normal climate, but both climates have considerable variability in the 20-year average values. The average net evaporation (evaporation minus precipitation) is 8.4 inches for the wet climate and 10.1 inches for the normal climate.

Generated 20-year average annual gaged inflow data for the two climatic periods are shown in figure 46. The long-term mean for the wet climate is about 110,000 acre-feet, and the long-term mean for the normal climate is about 22,000 acre-feet. Thus, a 17-percent decrease in net evaporation (from 10.1 to 8.4 inches) produces a 400-percent increase in inflow. Extreme sensitivity of runoff to changes in net evaporation is a characteristic of many basins in the prairie pothole region of the north-central United States and south-central Canada. Although a 400-percent increase in average annual inflow might seem large, the corresponding net change in average annual runoff is small. An annual inflow of 22,000 acre-feet corresponds to 0.13 inch of runoff assuming a 3,320-square-mile contributing drainage area for the Devils Lake Basin, and an annual inflow of 110,000 acre-feet corresponds to 0.64 inch of runoff. Thus, the net change in annual runoff is only about 0.5 inch.

Generated annual maximum lake levels of Devils Lake for the two climatic periods are shown in figure 47. The 17-percent decrease in net evaporation and 400-percent increase in inflow to Devils Lake results in much higher lake levels for the wet climate than for the normal climate. For the wet climate, the level of Devils Lake exceeds 1,435 feet above sea level during most of the 5,000-year simulation period and is never less than 1,425 feet above sea level. For the normal climate, the level of Devils Lake is less than 1,425 feet above sea level during most of the simulation period and never exceeds 1,450 feet above sea level. For the wet climate, the level of Devils Lake exceeds the spill elevation to Stump Lake (1,446.5 feet above sea level) most of the time and, during 24 distinct time intervals, exceeds the spill elevation to the Sheyenne River (1,459.0 feet above sea level). During many of those time intervals, the level of Devils Lake exceeds the spill elevation by several feet. For the normal climate, the level of Devils Lake exceeds the spill elevation to Stump Lake during only one interval (not counting the first), and Devils Lake is essentially dry (1,400 feet above sea level or less) during seven time intervals.

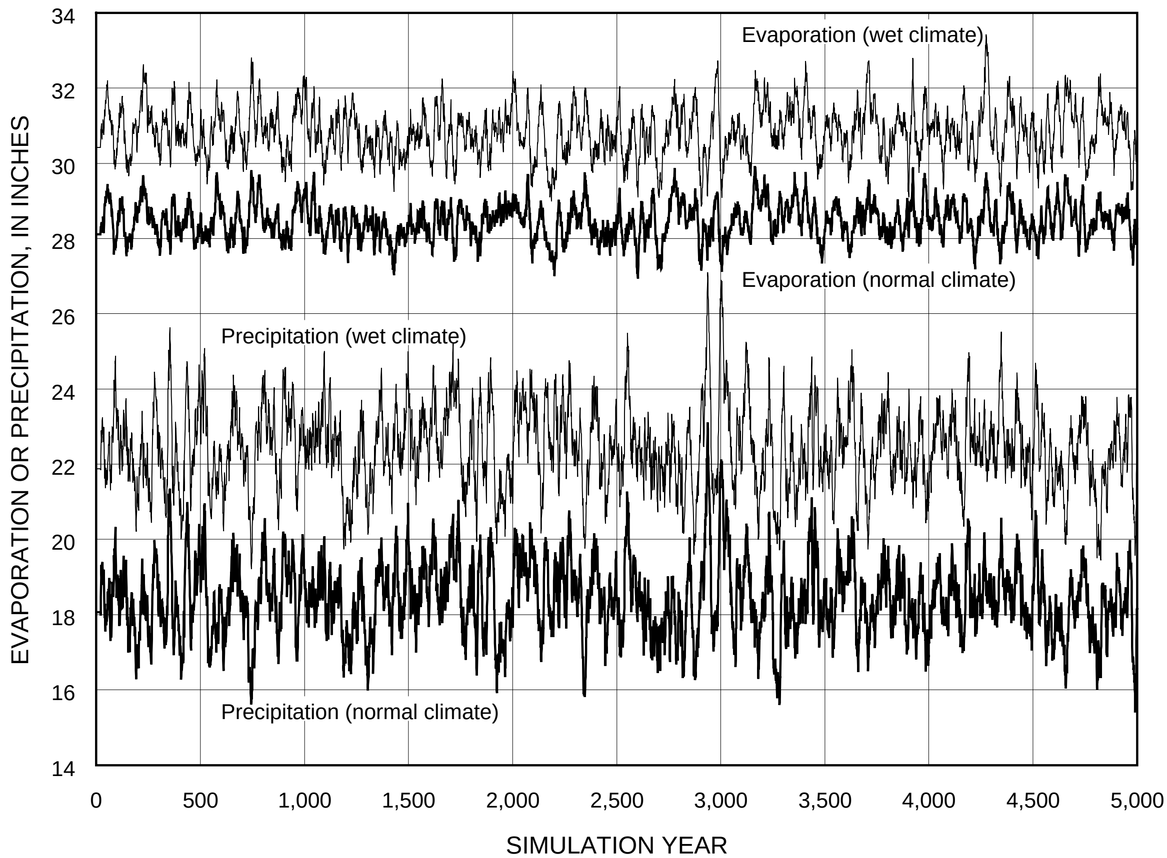

Figure 45. Generated 20-year average annual evaporation and precipitation for Devils Lake for wet climate (1980-99) and normal climate (1950-78).

Scientists with the North Dakota Geological Survey used radiocarbon dating of soils from the Jerusalem and Tolna Coulee Outlets (fig. 2) to reconstruct the lake-level fluctuations of Devils Lake since the end of glaciation, about 10,000 years ago (Bluemle, 1991; Murphy and others, 1997). The reconstructed record for before the past 2,500 years has several long gaps with limited information, and the temporal resolution is too coarse to determine the frequency of fluctuations required for this study. However, the history of lake-level fluctuations for the past 2,500 years (Bluemle, 1996) is more detailed and of particular interest for this study. Bluemle (1996) indicated three distinct time intervals during the past 2,500 years when Devils Lake was dry and two distinct time intervals when Devils Lake reached its natural spill elevation to the Sheyenne River. He also indicated five distinct time intervals during the past 2,500 years when Devils Lake spilled to Stump Lake and noted that Devils Lake "almost certainly" overflowed to Stump Lake several more times, but the data could not be used to determine exactly how often. Bluemle also stated "the natural condition for Devils Lake is either rising or falling, either toward overflow or dry lake bed."

Neither of the generated lake-level sequences shown in figure 47 reproduced the lake-level behavior indicated by Bluemle (1996). The wet-climate sequence produced much too high a frequency of spills and no instances when the lake was dry. The normal-climate sequence produced approximately the correct number of times when the lake was dry (seven times in 5,000 years compared to Bluemle’s estimate of three times in 2,500 years) but produced only one spill to Stump Lake and no spills to the Sheyenne River.

Although neither sequence, by itself, reproduced the geologic history of lake-level fluctuations, the full range of fluctuations was reproduced using a climatic history that consisted of long periods of climatic conditions similar to those during 1950-78 and occasional shorter periods of climatic conditions similar to those during 1980-99. Thus, conditions during the 1980-99 and 1950-78 climatic periods may represent the full range of climatic conditions that have occurred in the Devils Lake Basin. The severe drought that occurred during the 1930’s and 1940’s is consistent with the climatic

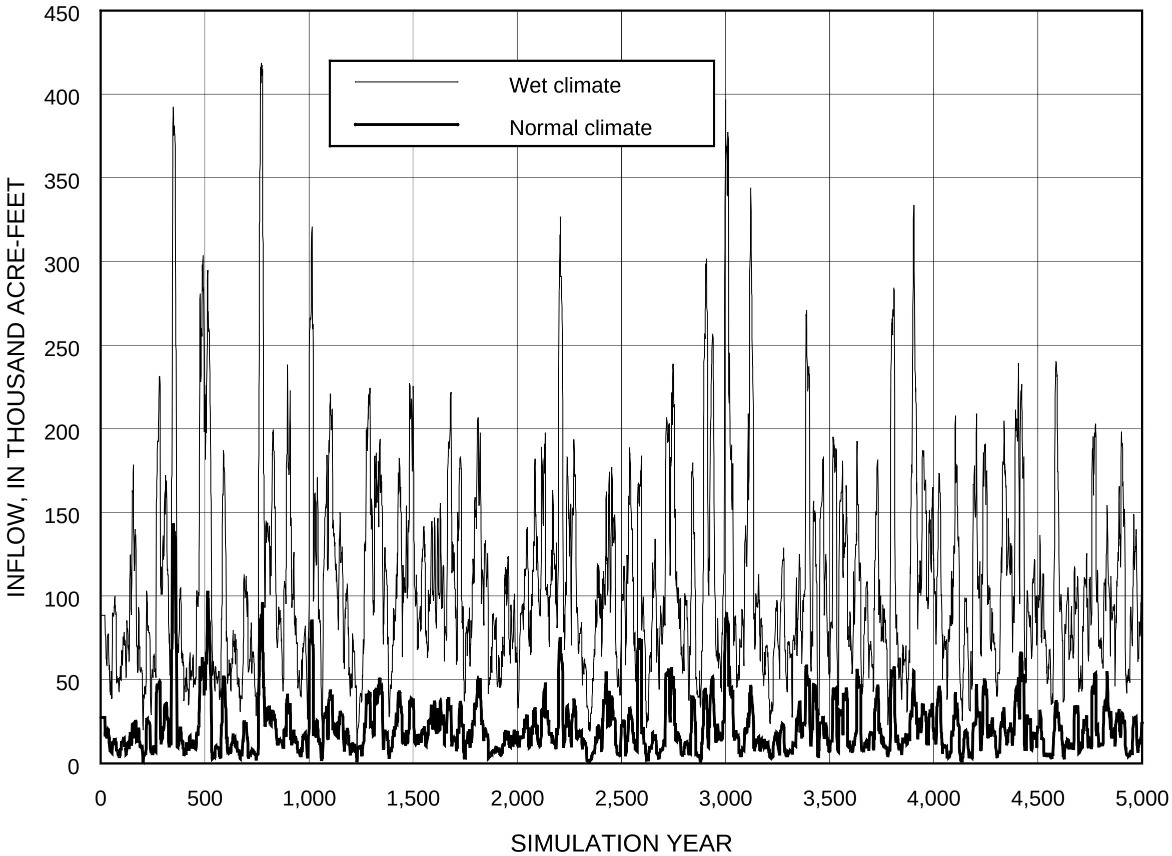

Figure 46. Generated 20-year average annual gaged inflow for Devils Lake for wet climate (1980-99) and normal climate (1950-78).

conditions that occurred during 1950-78 as indicated by the instances when the level of Devils Lake was less than 1,400 feet above sea level (fig. 47).

A study of precipitation in the African Sahel region (Demaree and Nicolis, 1990) showed a pattern of two "quasi-stable" climate regimes with randomly occurring jump transitions between the two regimes. They showed that such behavior is consistent with nonlinear dynamical models of long-term climatic fluctuations. In this study, a simple stochastic model was used to model the transition times between the wet and normal climates. The two parameters of the stochastic model are the average duration of the wet climatic period and the average duration of the normal climatic period. The parameters were adjusted so the lake-level fluctuations generated with the stochastic model were consistent with the lake-level fluctuations indicated by Bluemle (1996).

The stochastic model for the transition times is a two-state Markov chain (Ross, 1985) expressed as

$$\text{Prob[wet climate in year } t \text{ given wet climate in year } t-1] = \frac{1}{D_W}$$

$$\text{Prob[normal climate in year } t \text{ given wet climate in year } t-1] = 1-\frac{1}{D_W}$$

$$\text{Prob[normal climate in year } t \text{ given normal climate in year } t-1] = \frac{1}{D_N}$$

$$\text{Prob[wet climate in year } t \text{ given normal climate in year } t-1] = 1-\frac{1}{D_N}$$

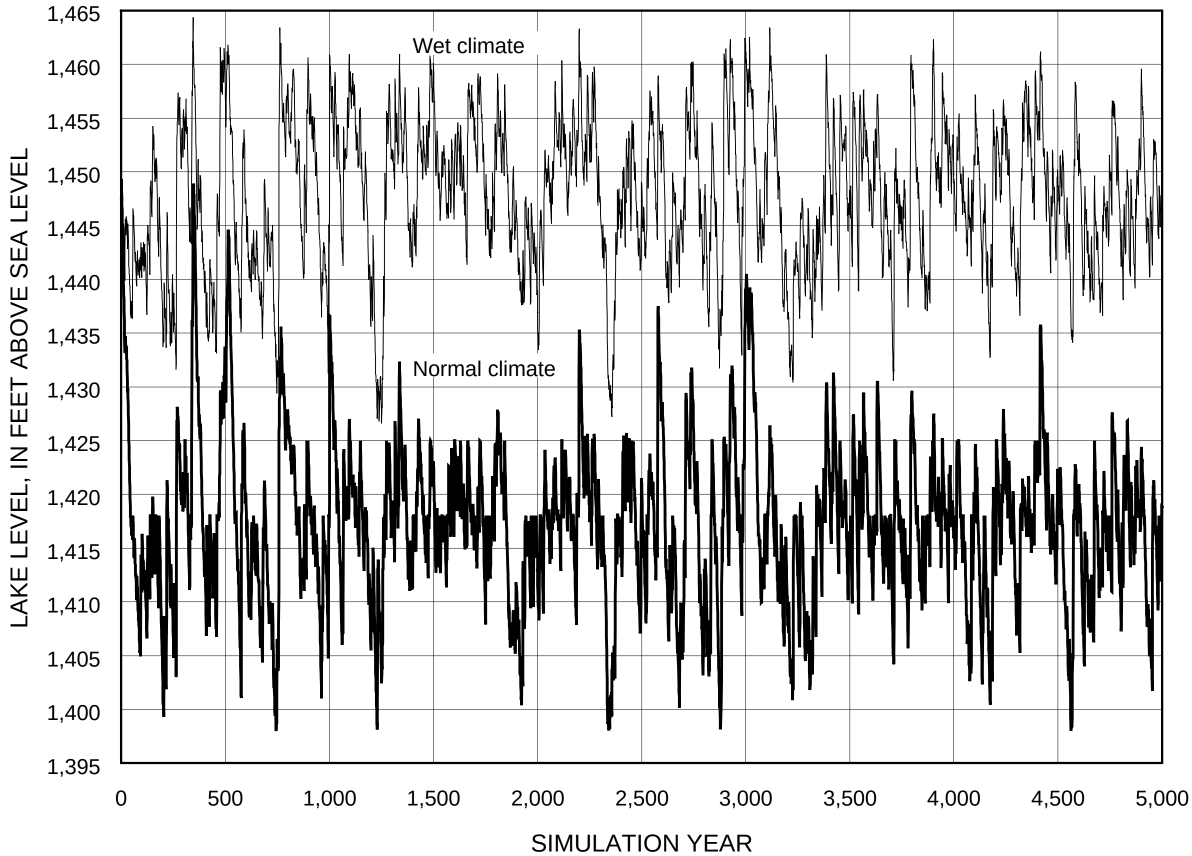

Figure 47. Generated annual maximum lake levels of Devils Lake for wet climate (1980-99) and normal climate (1950-78).

where

D_W is the average duration of the wet climatic period, in years; and

D_N is the average duration of the normal climatic period, in years.

For various values of the average duration times, a sequence of 5,000 years of monthly inputs was generated as described earlier except that the time-series models for the wet and normal climates alternated according to the Markov transition probabilities. A wet climate was assumed for the first year of the simulation period, and the subsequent climatic periods were generated at random from the Markov model. The frequencies of extreme lake levels then were determined for each combination of average duration times (table 16). The first two rows in table 16 correspond to the lake-level sequences shown in figure 47 for the wet climate (row 2) and the normal climate (row 1). Rows 3 through 6 show an average duration of 10 years for the wet climatic periods and an average duration of between 10 and 90 years for the normal climatic periods. The number of times Devils Lake dries up increases from zero to four as the average duration of the normal climatic periods increases, but the number of times Devils Lake spills to the Sheyenne River decreases from eight to two. Thus, the average duration of the wet climatic periods needs to be higher than 10 years. Rows 7 through 10 show an average duration of 20 years for the wet climatic periods and an average duration of between 20 and 180 years for the normal climatic periods. The number of times Devils Lake dries up increases from zero to the target of six, and the number of times Devils Lake spills to the Sheyenne River decreases from nine to the target of four. The frequencies of extremes obtained from average durations of either 120 or 180 years for the normal climatic periods (rows 9 and 10) are reasonable. The 180-year average duration matches the frequency of extreme low and extreme high lake levels exactly. However, the number of times Devils Lake spills to Stump Lake is too low. Therefore, the combination of 20 years for the average duration of the wet climatic periods and 120 years for the average duration of the normal climatic periods (row 9) was selected as the best combination for matching long-term lake-level frequencies. The combination of 40 years for the

Table 16. Frequency of extreme lake levels computed from generated 5,000-year sequences of annual maximum lake levels of Devils Lake

[>, greater than]

Row number	Average duration of wet climatic periods (similar to 1980-99) (years)	Average duration of normal climatic periods (similar to 1950-78) (years)	Number of times Devils Lake dries up (6)[1]	Number of times Devils Lake spills to Stump Lake (>10)[1]	Number of times Devils Lake spills to Sheyenne River (4)[1]
1	0	5,000	7	1	0
2	5,000	0	0	>40	24
3	10	10	0	34	8
4	10	30	1	21	4
5	10	60	2	15	2
6	10	90	4	9	2
7	20	20	0	29	9
8	20	60	3	26	6
9	20	120	5	12	5
10	20	180	6	8	4
11	40	40	1	31	8
12	40	120	5	16	6
13	40	240	5	12	4
14	40	360	5	8	2

[1]Approximate counts per 5,000 years based on geologic evidence (Bluemle, 1996).

average duration of the wet climatic periods and 240 years for the average duration of the normal climatic periods (row 13) also provides a good match to the long-term lake-level frequencies. However, the lake-level sequence for that combination indicates that the spills to Stump Lake tended to be clustered and Devils Lake did not spill to Stump Lake during two long time intervals (longer than 1,200 years). Thus, a 240-year average duration for the normal climatic periods probably is too long.

The generated inputs and lake levels for the combination of 20 years for the average duration of the wet climatic periods and 120 years for the average duration of the normal climatic periods are shown in figures 48 through 50. The 20-year average annual gaged inflow (fig. 49) is characterized by long intervals of low to moderate values (less than 120,000 acre-feet) and short bursts of very high values. The four highest values exceed 266,000 acre-feet, which is the average annual inflow from Big Coulee and Channel A for 1993-99. Therefore, during several periods before recorded history, inflows probably were as high or higher than recent inflows for more than 20 years. The generated annual maximum lake levels (fig. 50) support Bluemle’s observation (1996) that the lake tends to be either rising or falling and does not fluctuate within a narrow range of levels for long time intervals. As shown in figure 3 (and indicated in the introduction), lake levels generally declined from 1867 to 1940 and then generally increased from 1940 to 2001. Those periods were bracketed by lake levels greater than 1,440 feet above sea level. Several similar cycles are evident in the generated data (for example, see simulation years 1,150 to 1,300; 1,800 to 2,000; and 2,200 to 2,400). The five spills to the Sheyenne River (fig. 50) correspond to the short bursts of very high inflow (fig. 49) that, in turn, correspond to wet periods that lasted longer than 20 years.

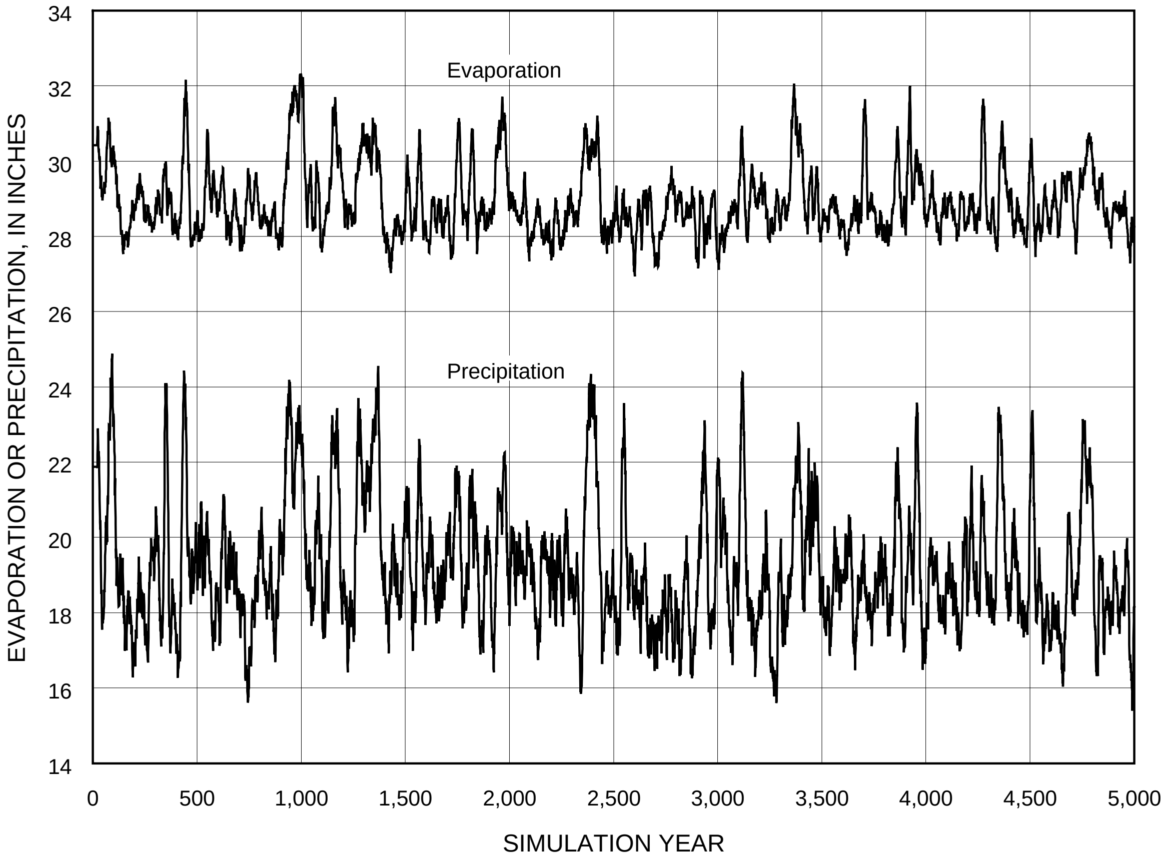

Figure 48. Generated 20-year average annual evaporation and precipitation for Devils Lake for mixed wet and normal climates.

Conditional Lake-Level Probability Analysis

The time-series model with mixed wet and normal climates in which the average duration of the wet periods is 20 years and the average duration of the normal periods is 120 years can be used to determine the probabilities of potential future lake levels for a specific time period given the current starting lake level. For example, the Devils Lake Basin currently is in the midst of a wet climatic period and the lake level on October 1, 2000, was 1,446.0 feet above sea level. The generated annual maximum lake levels of Devils Lake (fig. 50) indicate that similar conditions can be expected to occur about 15 times in 5,000 years or about once every 330 years (indicated in the figure by years in which the level of Devils Lake is rising and first exceeds 1,445 feet above sea level). In 5 of the 15 instances, the lake continues to rise to its natural spill elevation before declining. Thus, the chance that Devils Lake will continue to rise to its spill elevation in the near future appears to be about 1 in 3. However, starting conditions for each of the 15 years are not exactly the same as conditions that existed on October 1, 2000. For example, the current wet cycle already has lasted 20 years and, compared to conditions in other more extreme years, such as 1997, the basin was relatively dry and runoff was relatively low at the beginning of water year 2001. Thus, to accurately compute conditional lake-level probabilities for water years 2001-50, the time-series model was used to generate 10,000 independent sequences of monthly inputs beginning with the same starting conditions that existed on October 1, 2000. The 10,000 sequences of inputs were used in the water mass-balance model to compute 10,000 lake-level sequences, or traces, beginning with the known lake level on October 1, 2000. By generating such a large number of conditional lake-level traces, estimates of future lake-level probabilities can be determined for virtually any conceivable scenario.

The duration of the current wet cycle is the most important factor in determining lake-level probabilities for the next 50 years. For the time-series model, the duration is assumed to be a random variable. Furthermore, the number of years into the future that the current wet cycle continues is independent of the year in which the wet cycle started (in this case, 1980). Thus, the distribution of the waiting time until the current wet cycle ends is a geometric distribution with a mean of

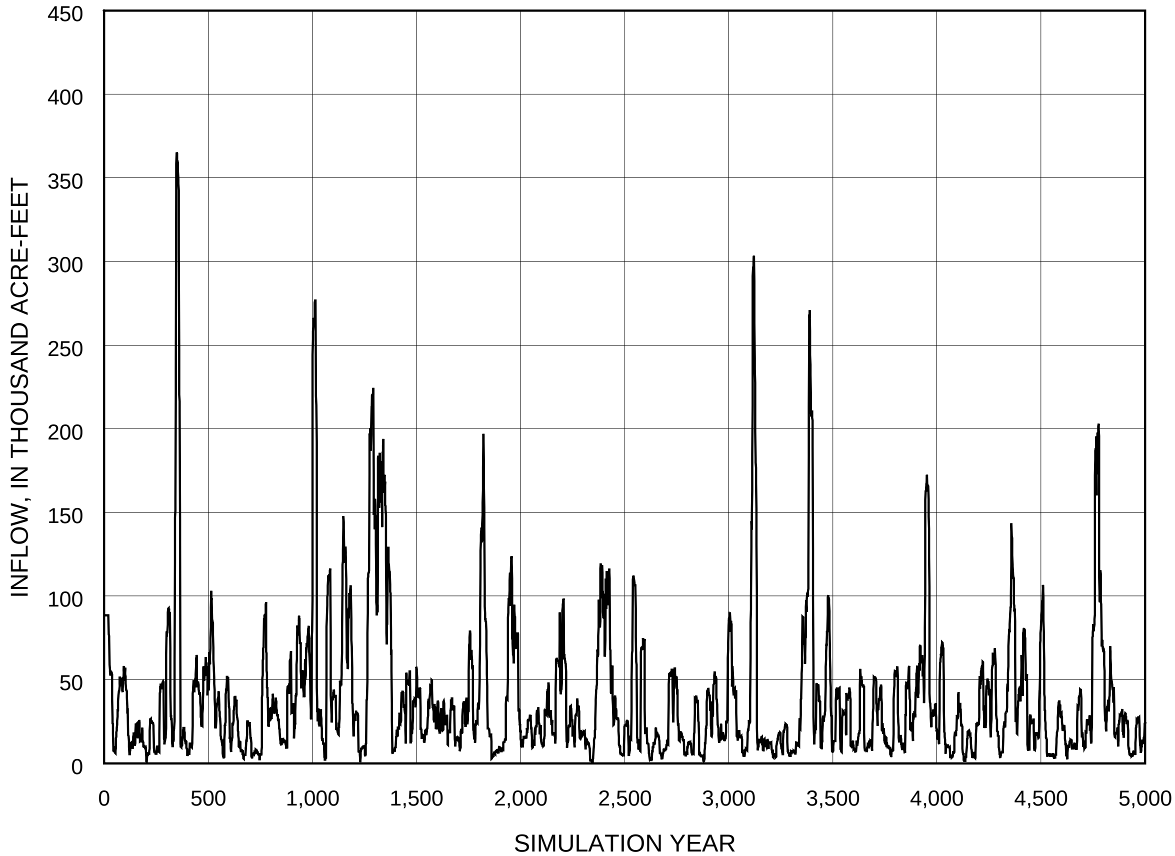

Figure 49. Generated 20-year average annual gaged inflow for Devils Lake for mixed wet and normal climates.

20 years. The probabilities that the wet cycle will end in or before various future years are given in table 17. The chance the wet cycle will end by 2005 is 23 percent, the chance it will end by 2015 is 54 percent, and the chance it will end by 2030 is 79 percent. These probabilities, however, are based on the assumption the Markov model is correct. Although the Markov model does reproduce the geologic history of lake-level fluctuations, the model is based on the simplifying assumption that the transition probabilities have not changed through time and that the two climatic periods represented by 1980-99 and 1950-78 are the only possible climatic periods.

Development of a model to predict future climatic conditions in the Devils Lake Basin is beyond the scope of this study. However, the links between global atmospheric circulation patterns and regional climate variability in North America have been explored in other studies. Studies of direct relevance to Devils Lake are Baldwin and Lall (2000) and Osborne (2000). Baldwin and Lall (2000) investigated the connections between Devils Lake climate and global atmospheric circulation patterns in an effort to forecast future lake levels. They concluded that climate in the Devils Lake Basin changes in response to global atmospheric circulation patterns and identified several key trends in hydroclimatic variables in the Devils Lake Basin. However, they also concluded that predicting future lake levels is beyond the current state of the art of hydroclimatic modeling. Osborne (2000) explored the impacts of regional climate variability in the Red River Basin and showed how changes in the position and strength of atmospheric pressure anomalies in the northern Pacific and Atlantic Oceans cause changes in the position of the jet stream over the United States and Canada. Changes in the position of the jet stream, in turn, cause changes in precipitation and temperature patterns in the Red River Basin. In particular, Osborne noted an increase in the frequency of a southwesterly flow of the jet stream over the Red River Basin since the late 1970’s, causing a general increase in precipitation and temperature in many months. He stated that, although the duration of the current wet conditions cannot be predicted exactly, "the total time to pass through the present ‘wet cycle’ will likely last beyond the first decade of the new century and extend to the year 2015."

The probabilities indicated in table 17 are consistent with Osborne’s (2000) prediction that the current wet cycle likely will last many more years. The Markov model indicates about a 50-percent chance the wet cycle will last beyond 2014 and

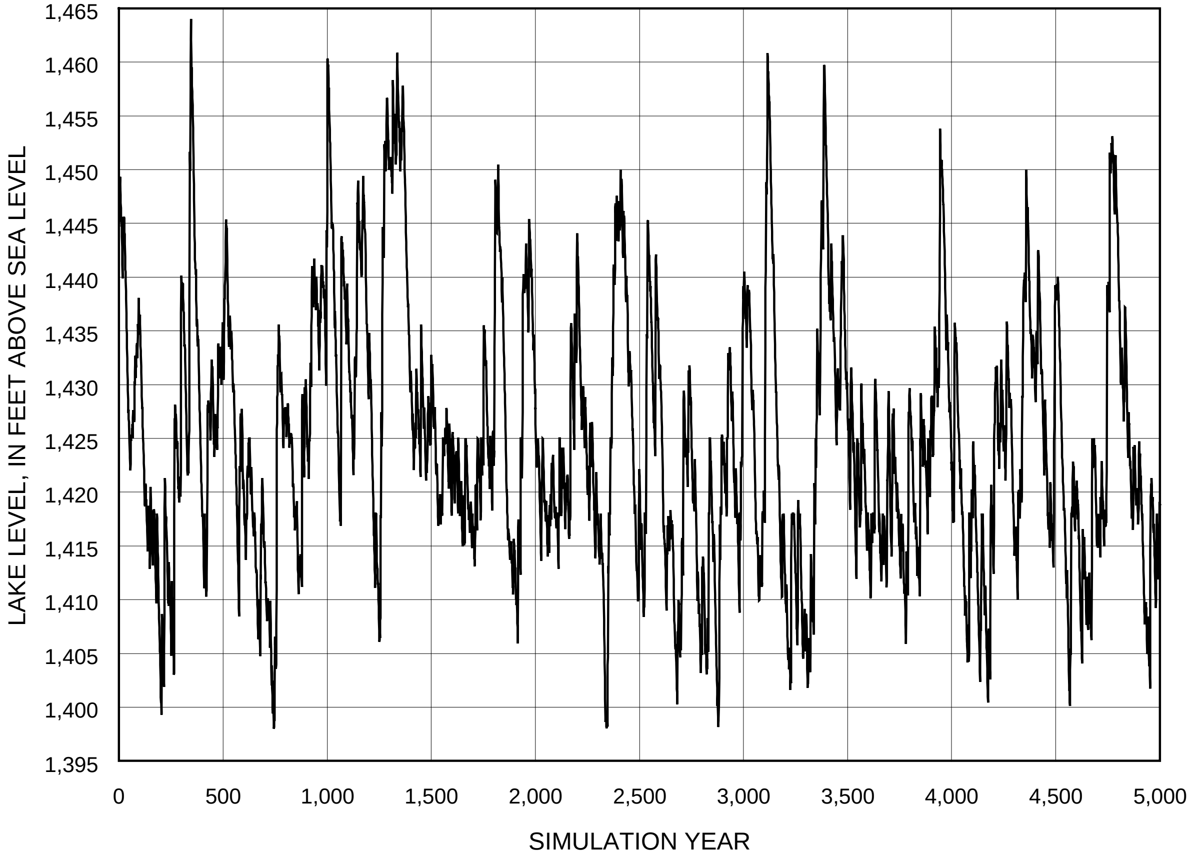

Figure 50. Generated annual maximum lake levels of Devils Lake for mixed wet and normal climates.

also indicates the wet cycle is not likely to end anytime soon (for example, the chance it will end by 2005 is only 23 percent) and is not likely to extend beyond 2030 (a 21-percent chance). In the conditional lake-level probability analysis, the duration of the current wet cycle was generated at random for each of the 10,000 model runs. The Corps' analysis of the economic benefits and environmental effects of a potential outlet (U.S. Army Corps of Engineers, 2002) is based on the assumptions that the wet cycle will last until 2015 and climatic conditions during 2016-50 will be similar to average climatic conditions for 1950-99. The conditional lake-level probabilities computed using the Corps' assumptions were similar to those computed using the Markov model.

Percentiles of generated lake levels for water years 2001-50 for the baseline condition are shown in figure 51. The percentiles were computed separately for each year and, thus, provide information on the probability distribution of future lake levels in any given year but cannot be used to compute probabilities associated with multiyear events. For example, in 2015, 10 percent (1,000) of the conditional lake-level traces generated using the Markov model exceeded about 1,453 feet above sea level. The percentiles computed using the Corps' assumptions were similar to those computed using the Markov model. However, lake levels generated using the Corps' assumptions tended to be higher during 2001-20 and lower during 2021-50 than lake levels generated using the Markov model. The lake levels generated using the Corps' assumptions tend to remain high until 2015 and then decline after the wet cycle ends, but the lake levels generated using the Markov model may decline sooner than 2015 (if the wet cycle ends sooner) or remain high well after 2015 (if the wet cycle ends later). For both sets of generated traces, the 50th-percentile curves decline slowly during 2001-50 and remain below the peak historical lake level of 1,448.0 feet above sea level attained in 2001.

The 10th-percentile curves shown in figure 51 are similar and indicate a 90-percent chance that lake levels during any of the next 50 years will be greater than 1,420 feet above sea level. The 1st-percentile curve obtained using the Corps' assumptions declines more rapidly than the 1st-percentile curve obtained using the Markov model. Thus, the chance of extremely low lake levels is higher with the Corps' assumptions than with the Markov model. The generated traces that are below the 1st percentile consist primarily of traces for which evaporation was the dominant component of the water

Table 17. Probability distribution of year in which current Devils Lake wet cycle will end based on Markov model

Year (y)	Probability that wet cycle will end in or before year y
2001	0.05
2002	.10
2003	.14
2004	.19
2005	.23
2006	.26
2007	.30
2008	.34
2009	.37
2010	.40
2011	.43
2012	.46
2013	.49
2014	.51
2015	.54
2020	.64
2025	.72
2030	.79
2035	.83
2040	.87

balance. Evaporation for the Corps' traces after 2015 was generated using average climatic conditions for 1950-99 and tends to be higher than evaporation for the normal climatic period (1950-78) used for the Markov model. Thus, the chance of extremely low lake levels during the latter years of the simulation period is higher with the Corps' assumptions.

Stochastic Outlet Simulation Analysis

The simulation results described in this section are based on the 10,000 generated sequences of monthly water-balance data described previously and were obtained using the Markov model to generate the duration of the current wet cycle. Each sequence of monthly water-balance data used to compute future lake levels for the baseline condition also was used to compute future lake levels for the outlet alternative identified by the Corps as the preferred alternative for detailed design and engineering analysis (U.S. Army Corps of Engineers, 2002). The Corps selected the single outlet alternative on the basis of economic evaluations of the benefits and costs of the various outlet alternatives, the effects of the outlet on downstream water quality, and numerous social and environmental considerations. The selected alternative (table 18) consists of a Pelican Lake outlet with a 300-cubic-foot-per-second pump capacity, a 600-cubic-foot-per-second Sheyenne River channel-capacity constraint, and a 450-milligram-per-liter Sheyenne River sulfate constraint. The selected alternative is similar to the Pelican Lake outlet described in table 8 except that the Highway 57 mixing barrier is not included. The 450-milligram-per-liter sulfate constraint may be lowered at a later time, if necessary, to lessen downstream

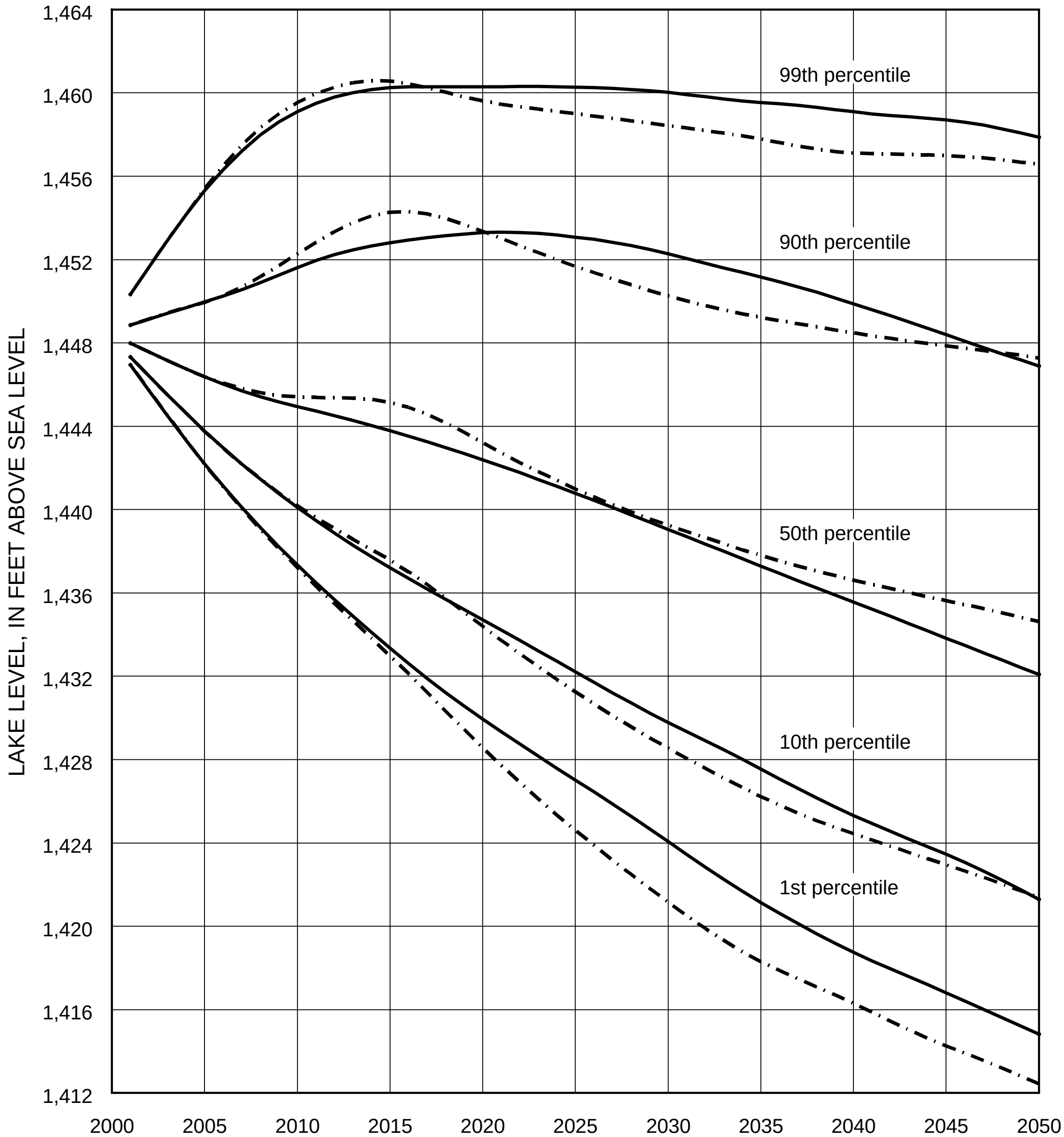

Figure 51. Percentiles of generated lake levels of Devils Lake for water years 2001-50 for baseline condition. (Solid lines indicate percentiles generated using Markov model to randomly select duration of current wet cycle, and dashed lines indicate exceedance levels generated using U.S. Army Corps of Engineers assumption that the current wet cycle will last until 2015.)

water-quality concerns. Other aspects of the selected outlet design also may be modified as detailed design and environmental impact assessments are completed by the Corps.

A 300-cubic-foot-per-second Pelican Lake outlet could potentially result in economic and social benefits far in excess of the estimated $98 million cost of the outlet (U.S. Army Corps of Engineers, 2002). For example, in recent years significant costs have been incurred for road raises and other infrastructure-protection measures in response to the rising lake, and many critical features have been protected to lake levels considerably higher than the recorded peak (1,448.0 feet above sea level). Highway 19 is protected to 1,455 feet above sea level, Highway 57 is protected to 1,456 feet above sea level, and the levees for the city of Devils Lake are protected to a still-water lake level of 1,454 feet above sea level. However, if Devils Lake rises another 10 feet, to a level of 1,458 feet above sea level, more than $975 million in additional costs or damages would occur (U.S. Army Corps of Engineers, 2002). An uncontrolled spill to the Sheyenne River also could result in major flood damages and adverse environmental effects downstream that are only beginning to be

Table 18. Constraints for stochastic simulation

	Constraints
Pump capacity	300 cubic feet per second
Pumping window	May 1 through November 30
Sheyenne River channel capacity	600 cubic feet per second
Sheyenne River sulfate constraint	450 milligrams per liter
Starting date for Channel A diversion	October 1, 2002
Starting date for outlet operation	May 1, 2005
Trigger elevation	1,441.4 feet above sea level
Water source	Pelican Lake

determined. Thus, the ability of the outlet to reduce peak lake levels if Devils Lake continues to rise several more feet in the coming years needed to be evaluated.

To compute future lake levels of Devils Lake, daily streamflows and sulfate concentrations for the Sheyenne River and daily outlet discharges and sulfate concentrations for Devils Lake were generated for each of the 10,000 sequences of monthly water-balance data. The discharges and sulfate concentrations were generated using the same methods as those described in a previous section for the wet scenario. However, for the stochastic analysis, the generated daily streamflows for the Sheyenne River needed to be consistent with the generated monthly water-balance data for Devils Lake for each of the 10,000 sequences. Therefore, a procedure was developed to use recorded streamflows for the Sheyenne River for 1970-99 to generate the daily streamflows for the Sheyenne River. That period was chosen because daily ambient streamflows for various locations from the outlet insertion point downstream to the Canadian border also were required for the Corps' downstream water-quality simulations, and the downstream streamflows needed to be calculated using recorded daily streamflows for 1970-99 to be compatible with the Corps' HEC-5Q computer model. The procedure used to generate the streamflows for the Sheyenne River is described in appendix A.

The effectiveness of the proposed outlet for reducing future peak lake levels of Devils Lake is shown in figure 52. The upper envelope curves for a given year were computed using the maximum lake level for each trace from 2001 to the given year. As indicated by the envelope curve that corresponds to the baseline-condition 10-percent exceedance probability, a 10-percent chance exists for the lake level to exceed 1,456.2 feet above sea level by 2020 without the outlet and 1,453.6 feet above sea level by 2020 with the outlet. The effectiveness of the outlet for reducing the envelope curves increases as the time interval increases. For 2050, a 10-percent chance exists for the lake level to exceed 1,459.4 feet above sea level without the outlet and 1,455.7 feet above sea level with the outlet.

The outlet is less effective in reducing the envelope curve for the 1-percent exceedance probability than for the higher exceedance probabilities (fig. 52). For the baseline condition, a 1-percent chance exists for the lake level to exceed 1,463.6 feet above sea level--4.6 feet above the spill elevation to the Sheyenne River--by 2050. Because the extremely high inflow volumes required to raise the lake to such high levels tend to overwhelm the outlet capacity, the outlet reduces the corresponding lake level by less than 1 foot. To increase the effectiveness of the outlet for reducing such extreme lake levels, the outlet capacity would need to be increased.

The chance that Devils Lake will continue to rise several more feet in the next few decades, with or without an outlet, is greater than 20 percent (fig. 52). However, except in the extreme case when a rapid lake-level rise would overwhelm the outlet capacity, the outlet is effective for reducing the probability of high lake levels in the future.

In addition to providing lake-level probabilities, the stochastic traces also provide valuable information on outlet performance for individual traces or groups of traces. One measure of outlet performance on a trace-by-trace basis is the reduction in peak lake level (the difference between the maximum lake level for the baseline condition and the maximum lake level with an outlet). The reduction in peak lake level is highly variable from trace to trace and depends on when the

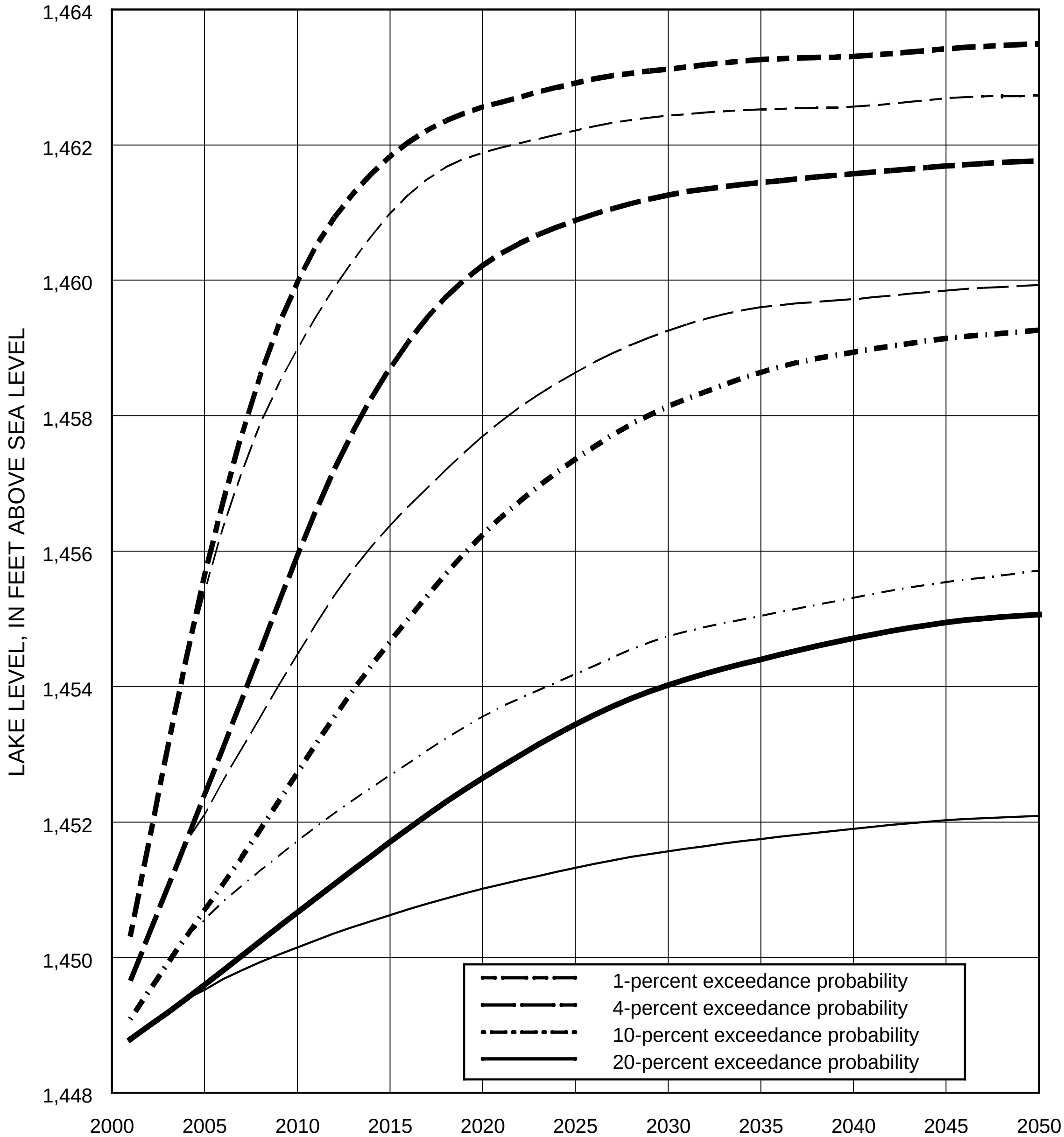

Figure 52. Upper envelope curves for the level of Devils Lake for water years 2001-50 for baseline condition and for 300-cubic-foot-per-second Pelican Lake outlet. (Heavy lines indicate baseline condition, and light lines indicate outlet.)

lake peaks, how high the lake peaks, how rapidly the lake rises, and so forth. For example, if the peak lake level for the baseline condition occurs during 2001-04, no reduction can occur because the outlet is not operational until 2005. In general, the later Devils Lake peaks, the more effective the outlet can be in reducing the peak. However, even if the lake peaks well after 2005, the lake may rise too slowly to maintain low sulfate concentrations in Pelican Lake. Thus, the outlet discharge would need to be reduced to meet the sulfate constraint, and the effectiveness of the outlet would be limited. Conversely, even if the outlet discharge is not restricted by the sulfate constraint, a rapid lake-level rise may overwhelm outlet capacity and, again, the effectiveness of the outlet would be limited.

The average reductions in the peak lake levels of Devils Lake for the generated traces are shown in figure 53. The curves were obtained by smoothing the reductions in peak lake levels from all 10,000 traces to obtain the average reductions for different peaks and different time intervals. The upper curve was obtained from all traces that peaked after 2015 (2,800 traces) and indicates that the average reduction was greater than 4 feet for traces that peaked between 1,456 and 1,460 feet above sea level for the baseline condition. The average reduction tends to decrease for peaks less than

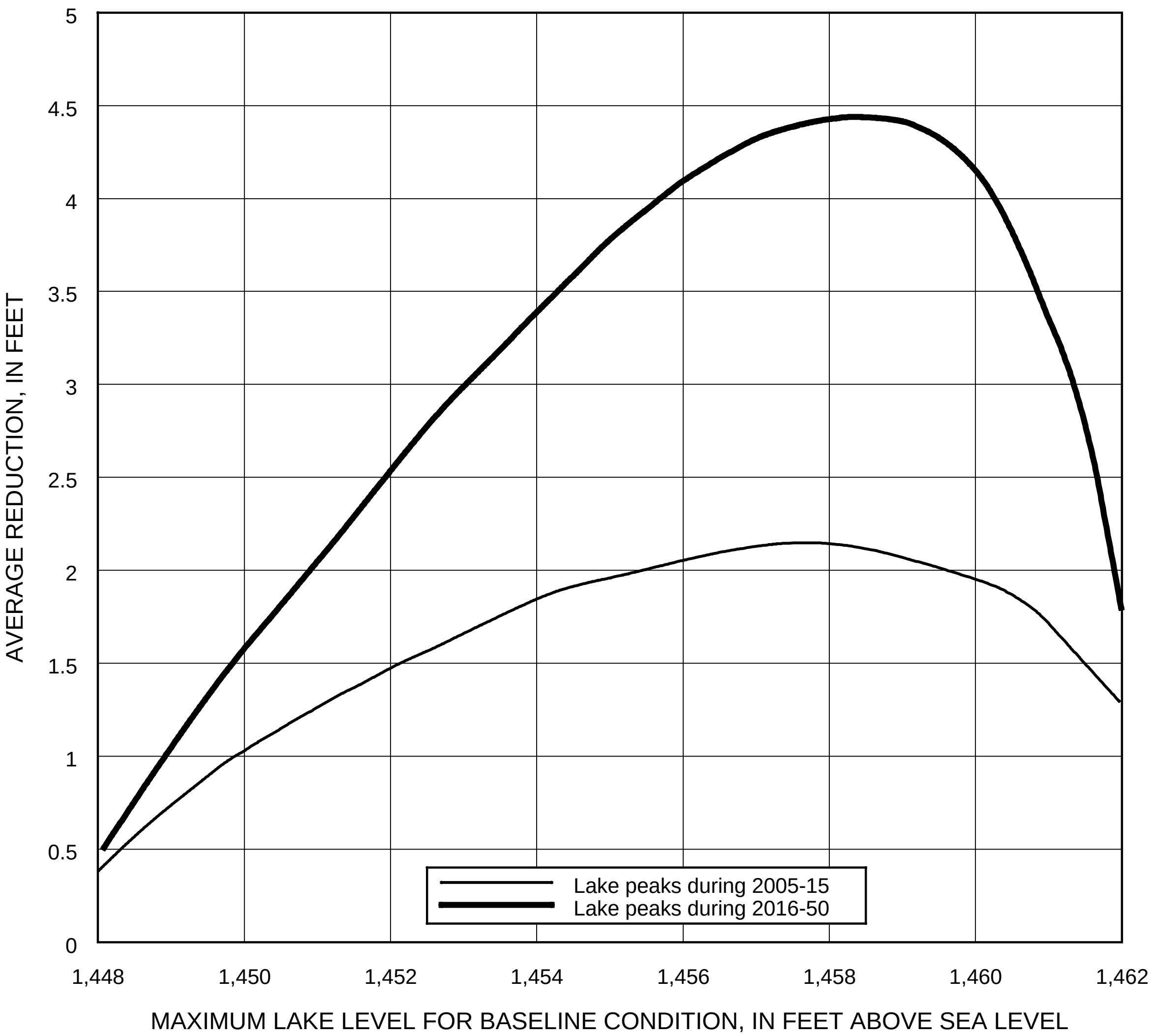

Figure 53. Average reductions in peak lake levels of Devils Lake for 300-cubic-foot-per-second Pelican Lake outlet.

1,456 feet above sea level because the sulfate constraint tends to reduce outlet discharges for many of those traces and for peaks greater than 1,460 feet above sea level because the lake levels for many of those traces rise too rapidly to be controlled by the outlet. The lower curve was obtained from all traces that peaked between 2005 and 2015 (2,800 traces) and indicates that the average reduction for those traces tends to be smaller than the average reduction for the traces that peaked after 2015. Many of these traces either peaked too early or rose too rapidly for the outlet to substantially reduce the peak. In 44 percent (4,400) of the 10,000 traces, the lake level peaked before 2005 and, thus, the outlet resulted in no reduction in the peak lake level.

An important consideration for the outlet is that the outlet does not hasten extreme lake-level declines or worsen in-lake water quality if drought conditions should occur in the future. Low lake levels and poor water quality would threaten the thriving fish population and result in adverse effects on the local economy. The effect of the outlet on low lake levels is shown in figure 54. The lower envelope curves for a given year were computed using the minimum lake level for each trace from 2001 to the given year. For the baseline condition, a 50-percent chance exists for the lake level to be less than 1,430 feet above sea level by 2050, and a 10-percent chance exists for the lake level to be less than 1,420.5 feet above sea level. Although a moderate (10-percent) chance exists for the lake to return to low levels comparable to those that existed during much of the 1900's (levels of less than 1,420 feet above sea level) by 2050, chances are greater that the lake will not fall to those levels until well beyond 2050. As indicated by the close correspondence between the baseline-condition curves and the outlet curves for the 10- and 1-percent nonexceedance probabilities, the Pelican Lake outlet has minimal effect on the probabilities of extremely low lake levels. The outlet ceases operation when lake levels fall below

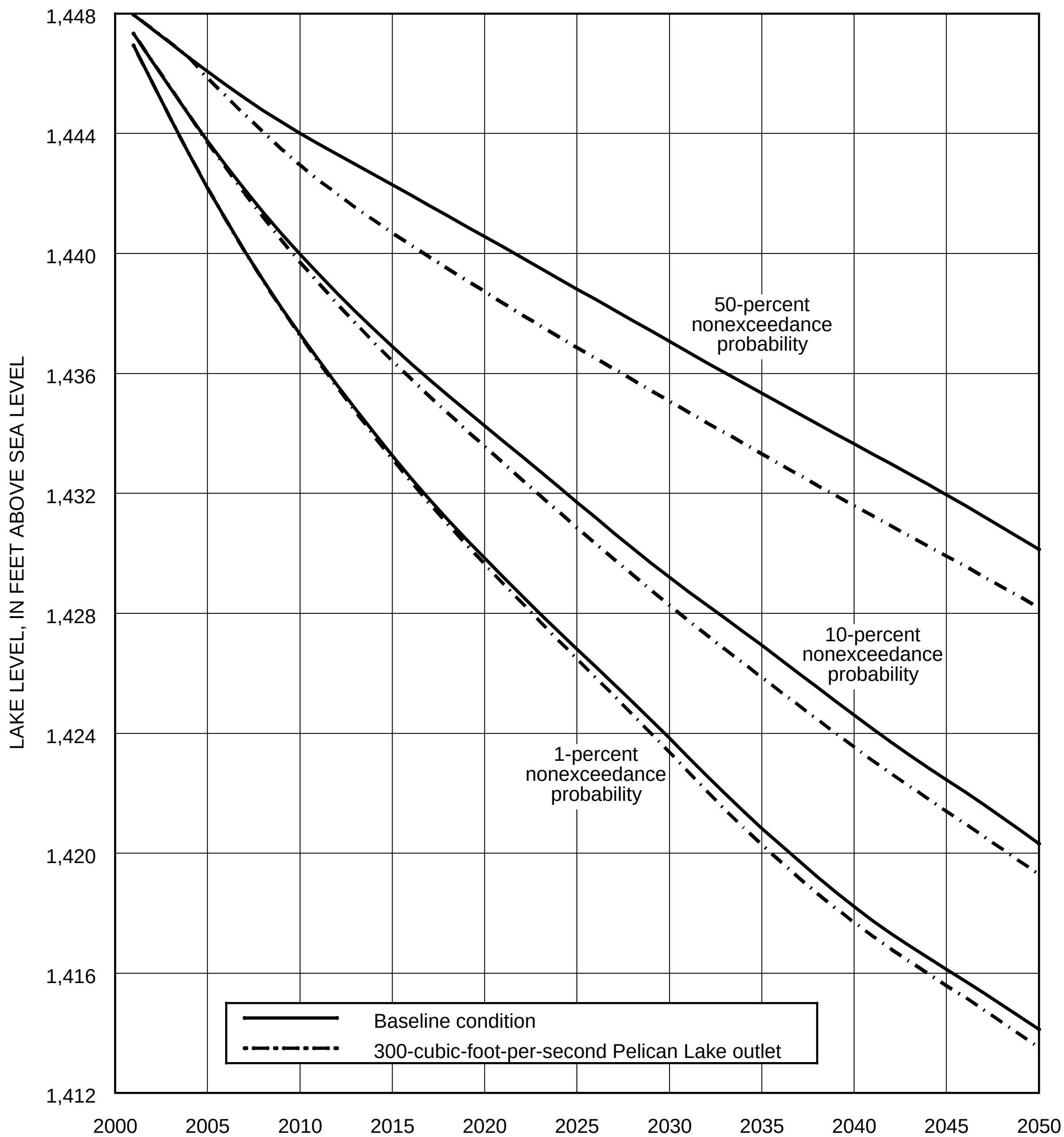

Figure 54. Lower envelope curves for the level of Devils Lake for water years 2001-50 for baseline condition and for 300-cubic-foot-per-second Pelican Lake outlet.

1,441.4 feet above sea level, and the outlet discharge may become severely limited by the sulfate constraint well before that level.

Upper envelope curves for the sulfate concentration of Main Bay are shown in figure 55. The outlet has negligible effect on the probabilities of high sulfate concentrations in Main Bay. Similar results (not shown) were obtained for each of the other lake boxes as well. Although sulfate concentrations may well exceed the high levels of the early 1990's (fig. 13) within the next 50 years, the outlet does not substantially increase the potential for poor in-lake water quality in the future.

SUMMARY

From 1993 to 2001, Devils Lake rose more than 25 feet, flooding farmland, roads, and structures around the lake and causing more than $400 million in damages in the Devils Lake Basin. In July 2001, the level of Devils Lake was at

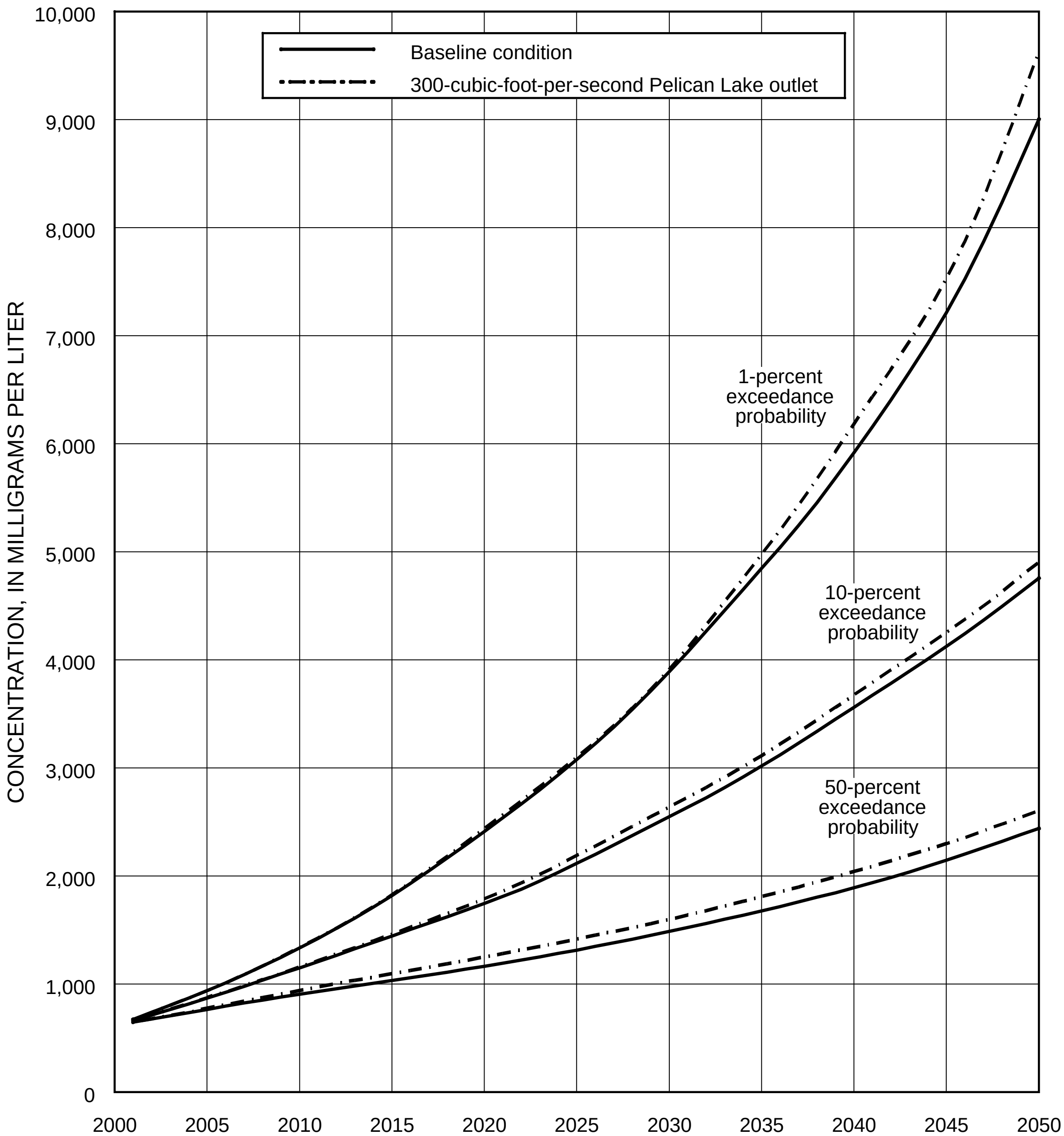

Figure 55. Upper envelope curves for dissolved sulfate concentrations for Main Bay for water years 2001-50 for baseline condition and for 300-cubic-foot-per-second Pelican Lake outlet.

1,448.0 feet above sea level, which was the highest lake level in more than 160 years. The lake could continue to rise to several feet above its natural spill elevation to the Sheyenne River (1,459 feet above sea level) in future years, causing extensive additional flooding in the basin and, in the event of an uncontrolled natural spill, downstream in the Red River of the North Basin as well. The outlet simulation model described in this report was developed in cooperation with the U.S. Army Corps of Engineers to determine the potential effects of various outlet alternatives on the future lake levels and water quality of Devils Lake.

Lake levels of Devils Lake are controlled largely by precipitation on the lake surface, evaporation from the lake surface, and surface inflow. For this study, a monthly water-balance model was developed to compute the change in total volume of Devils Lake, and a regression model was used to estimate monthly water-balance data on the basis of limited recorded data. Actual precipitation on the lake surface, evaporation from the lake surface, and surface inflow were estimated indirectly using published precipitation data from the National Weather Service precipitation gage at Devils Lake, evaporation data from a previous study, and lake-level records or daily mean discharge data from U.S. Geological Survey gaging stations. Estimated coefficients for the regression model indicated fitted precipitation on the lake surface was greater than measured precipitation in most months, especially February, March, and April, and fitted evaporation from the lake surface was less than previously estimated evaporation in most months. Ungaged inflow in most months was about 2 percent of gaged inflow except in March (93 percent), April (12 percent), and May (19 percent).

The quality of water in the various bays of Devils Lake differs even when Devils Lake is a single water body. Dissolved sulfate was considered to be the key water-quality constituent for evaluating the effects of a proposed outlet on downstream water quality. Detailed spatial water-quality sampling of Devils Lake indicated sulfate concentrations are relatively uniform within the bays, but large differences exist among the bays. To simulate the future operation and water-quality effects of an outlet from Devils Lake, detailed water and sulfate mass-balance models were developed to compute changes in sulfate load for each of six major storage compartments in response to precipitation, evaporation, inflow, and outflow from each compartment. The storage compartments--West Bay North, West Bay South, Main Bay, East Bay, East Devils Lake, and Stump Lake--were referred to as lake boxes. The lake boxes are connected by bridge openings, culverts, or natural channels that restrict mixing between the boxes. A numerical algorithm was developed to calculate inflow and outflow from each lake box such that the combined water balance for all the lake boxes was equivalent to the water balance for the combined Devils Lake and Stump Lake system.

Sulfate loads for the lake boxes first were calculated using the assumptions that no interaction occurred between the bottom sediments and the water column and no wind- or buoyancy-induced mixing occurred between lake boxes. However, the fitted sulfate loads did not agree with the estimated sulfate loads, which were obtained from recorded sulfate concentrations. About 350,000 tons of sulfate in Devils Lake during 1988-99 could not be accounted for by external loads from surface inflow. Most of the extra sulfate was determined to be from bottom sediments. Recorded data from bottom-sediment cores indicated the sulfate concentration of pore water below Devils Lake increased from west to east and from the sediment-lake interface to the deeper sediments. Therefore, three sediment layers were included in the sulfate mass-balance model. Each layer consisted of a series of sediment "boxes" from west to east, with each box representing approximately the same cross-section area. The sulfate concentrations in the boxes increased from west to east along the lake centerline and from shallow to deep sediment layers. The flux of sulfate between bottom sediments and the lake and between shallow sediments and deep sediments was controlled by the concentration gradient and by the porosity of the bottom sediments.

The sulfate mass-balance model with sediment interaction provided a good representation of the estimated sulfate load for Devils Lake for 1988-99. However, the distribution of sulfate loads among the lake boxes did not agree with the distribution of sulfate loads computed from historical sulfate concentrations. The model calculations resulted in too much sulfate in East Bay and East Devils Lake and not enough in Main Bay and West Bay at the end of 1999. The likely cause of the discrepancy was determined to be mixing between the lake boxes. Mixing can occur during periods of open water because of wind-induced head differences between lake boxes and during periods of ice cover because of water-density differences between lake boxes. Therefore, a hydrodynamic model was used to estimate average flow velocities between lake boxes for open-water and ice-covered conditions. The average flow velocities depended on lake level. The sulfate mass-balance model with sediment interaction was modified to include a component for exchange flows between lake boxes. Assuming perfect mixing between lake boxes (i.e., water that flows from one box to the next becomes perfectly mixed before flowing back) resulted in more uniform concentrations among the lake boxes at the end of the calibration period than was indicated by the historical data. Therefore, mixing coefficients were included to account for imperfect mixing at each of the lake-box connections. The mixing coefficients and the coefficients that control the flux of sulfate from bottom sediments were estimated jointly using a nonlinear regression model to minimize the differences between recorded and fitted sulfate concentrations for 1988-99. The fitted concentrations were in close agreement with the recorded concentrations.

After the water and sulfate mass-balance models were calibrated using historical data for 1980-99, the models could be used to calculate potential future lake levels and sulfate concentrations given starting lake levels and sulfate concentrations, starting sulfate concentrations in the sediment boxes, and future values of monthly precipitation, evaporation, and inflow. Of course, there is no way to predict exactly what future values of the water-balance inputs might be. One approach for generating potential future inputs is a scenario approach, in which historical values of the inputs are repeated in the future in a particular sequence. A "wet scenario" was developed for evaluating the effects of an outlet should Devils Lake continue to rise to its natural spill elevation in the next 20 years before subsiding. In the wet scenario, monthly precipitation, evaporation, and inflow for 1993-99 were assumed to occur in the future, back to back, for 21 years. Precipitation, evaporation, and inflow for 1981-99 and 1981-90 were used for the remaining 29 years of the 50-year simulation period. The future represented by the wet scenario was one in which a potential outlet could be most effective for reducing flood damages and minimizing adverse effects on downstream water quality. Thus, the wet scenario provided a useful basis for screening outlet alternatives because outlet alternatives that are not economically viable and environmentally acceptable (as determined by the U.S. Army Corps of Engineers' criteria) probably would not be acceptable for most other conceivable scenarios.

Simulating operation of virtually any outlet alternative was straightforward given the water and sulfate mass-balance models, future mass-balance model inputs (precipitation, evaporation, and inflow), and future daily flows and sulfate concentrations in the Sheyenne River. Future daily flows for the Sheyenne River for the wet scenario consisted of historical daily flows for the same sequence of years used for generating Devils Lake inflows. Future daily sulfate concentrations for the Sheyenne River were generated using a regression model relating sulfate concentration to daily flow, based on historical data for the Sheyenne River near Warwick. Four outlet alternatives--two for West Bay and two for Pelican Lake--were evaluated using data from the outlet simulation model. Simulation results indicated neither of the West Bay outlet alternatives provided effective flood-damage reduction without exceeding downstream water-quality constraints. However, both Pelican Lake outlet alternatives were promising alternatives for future consideration. For both alternatives, Channel A flows were assumed to be rerouted through the pre-1979 flow path into Big Coulee. The alternatives differed according to future actions assumed for Highway 19. In the first Pelican Lake outlet alternative, Highway 19 is not used to control the level of Pelican Lake. Therefore, as pumping occurs, the lake level north of Highway 19 may recede below the lake level south of Highway 19, and water may flow from south to north to equalize the lake levels. In the modified Pelican Lake outlet alternative, Highway 19 is used to control the flow of water from south to north into Pelican Lake. Therefore, pumping can cause the lake level north of Highway 19 to fall below the level south of Highway 19. The Pelican Lake outlet with a 300-cubic-foot-per-second pump capacity and 250-milligram-per-liter sulfate constraint and the modified Pelican Lake outlet with a 480-cubic-foot-per-second pump capacity and 250-milligram-per-liter sulfate constraint both provided significant flood-damage reduction with only minor downstream water-quality changes. The Pelican Lake outlet provides less flood protection than the modified Pelican Lake outlet, but the smaller pump capacity also was less costly than the 480-cubic-foot-per-second pump capacity.

The wet scenario was used to evaluate the effectiveness of various outlet alternatives, but no evaluation was made as to the likelihood that such a scenario might actually occur. Therefore, a statistical time-series model was developed to generate monthly water mass-balance data that could, in turn, be used to probabilistically evaluate outlet performance. The time-series model was calibrated using estimated monthly water-balance data for 1980-99 because that period represented a statistically homogeneous climatic period. A pronounced and highly significant change toward wetter climatic conditions occurred in the late 1970's as a result of changes in atmospheric circulation patterns. Therefore, data from before 1980 were not representative of recent climatic conditions. The time-series model provided a good representation of the statistical properties of precipitation, evaporation, and inflow for the 1980-99 calibration period.

The time-series model could be used to generate potential future inputs, assuming that future climatic conditions are similar to the 1980-99 calibration period. Links between global atmospheric circulation patterns and regional climate variability in the Devils Lake Basin indicate the current wet conditions are likely to last many more years, perhaps to 2015 and beyond. However, the duration of the current wet cycle cannot be predicted exactly. Therefore, the time-series model was modified to allow inputs to be generated that reflect potential climate nonstationarity. Precipitation, evaporation, and inflow data for 1950-78 were used as a cross-validation data set. With minor modifications, the time-series model worked equally well for generating inputs for both the 1980-99 calibration period and the 1950-78 cross-validation period. The geologic history of lake-level fluctuations of Devils Lake for the past 2,500 years was consistent with a climatic history that consisted of two climate "states"--a wet state, similar to conditions during 1980-99--and a normal state, similar to conditions during 1950-78. The transition times between the wet and normal climatic periods occur randomly, but the durations of the normal climatic periods are much longer, on average, than the durations of the wet climatic periods. The best representation of the geologic history was obtained using an average duration of 20 years for the wet climatic periods and 120 years for the normal climatic periods. A stochastic model, called a Markov model, was used to randomly generate the transition times between the two climatic periods.

The statistical time-series models for the wet and normal climates were used in conjunction with the Markov model to generate 10,000 independent sequences of monthly precipitation, evaporation, and inflow inputs for Devils Lake for 2001-50. The sequences of inputs then were used in the water and sulfate mass-balance models to generate 10,000 sequences, or traces, of lake levels and sulfate concentrations for Devils Lake for water years 2001-50. Each trace began with the same starting conditions that existed at the beginning of the simulation period.

Each of the 10,000 generated sequences of monthly water-balance inputs were used to compute future lake levels and sulfate concentrations for the baseline (natural) condition and for the outlet alternatives identified by the U.S. Army Corps of Engineers as the preferred alternative for detailed design and engineering analysis. The selected alternative consists of a Pelican Lake outlet with a 300-cubic-foot-per-second capacity and a 450-milligram-per-liter sulfate constraint. The outlet significantly lowered the probabilities of future lake-level increases. For example, without an outlet, a 10-percent chance exists that Devils Lake will rise above its natural spill elevation (1,459 feet above sea level) within the next 50 years. With an outlet, a 10-percent chance exists that Devils Lake will rise above 1,455.7 feet above sea level within the next 50 years. The outlet did not substantially increase the probabilities of reaching low lake levels or poor water-quality conditions during the next 50 years.

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APPENDIX A

Elevation/Area/Volume Equations for Lake Boxes

The areas of the individual lake boxes at various elevations were obtained from several sources (table A1); however, no consistent method exists for interpolating between known areas or for converting areas to volumes. Therefore, to simplify the water mass-balance

Table A1. Areas used to calibrate elevation/area equations for lake boxes

[Areas for West Bay North and West Bay South were supplied by the North Dakota State Water Commission, and areas for other lake boxes were supplied by the U.S. Army Corps of Engineers]

Elevation (feet above sea level)	West Bay North (acres)	West Bay South (acres)	Main Bay (acres)	East Bay (acres)	East Devils Lake (acres)	Stump Lake (acres)
1,400	0	0	4,780	0	--	6,300
1,405	0	0	10,000	0	3,250	6,900
1,410	0	0	12,000	4,500	3,620	7,400
1,415	0	0	14,800	12,800	3,900	8,000
1,420	0	4,120	17,100	14,700	4,150	8,700
1,425	0	10,500	18,700	17,100	4,400	9,500
1,430	0	17,800	19,800	18,500	4,600	10,600
1,435	2,910	22,900	21,100	20,700	4,800	11,500
1,440	7,160	25,970	22,800	25,100	5,000	13,270
1,445	28,500	28,880	25,000	27,300	7,000	--
1,450	53,560	32,110	--	--	--	--
1,457.5	120,760	37,000	32,500	34,750	9,000	22,000

model computations, a set of equations was developed for relating elevations, areas, and volumes. The starting point for all six boxes was a general equation for volume as a function of elevation. The general equation is

$$V(h) = V_s\left[\frac{ah^* + \left(\frac{1}{2}\right)(1-a)(1+b)(1-\cos\{\pi h^*\})}{(1-b\cos\{\pi h^*\})}\right]^{c+1}$$

where

$V(h)$ is volume, in acre-feet;

h is lake-surface elevation, in feet above sea level;

$V_s = V(1,457.5)$ is a volume scaling factor;

$a > 0$, $b > -1$, and $c > 0$ are shape parameters that are fitted separately for each bay;

$h^* = \frac{[h - h_{min}]}{[1,457.5 - h_{min}]}$ is a dimensionless elevation $(0 < h^*)$; and

h_{min} is the minimum (dry lakebed) elevation $(h_{min} < h)$.

$V(h_{min}) = 0$, and $V(h)$ has positive first and second derivatives for $h > h_{min}$, which are conditions that must be satisfied by a valid volume function. The area equation can be obtained by differentiating $V(h)$,

$$A(h) = \left(\frac{d}{dh}\right)V(h) = A_s\left[1 + \frac{\left(\frac{\pi}{2a}\right)(1-a)(1+b)(1-b)\sin\{\pi h^*\}}{(1-b\cos\{\pi h^*\})^2}\right]\left[ah^* + \frac{\left(\frac{1}{2}\right)(1-a)(1+b)(1-\cos\{\pi h^*\})}{(1-b\cos\{\pi h^*\})}\right]^c$$

where

$A_s = A(1,457.5) = V_s\frac{a(c+1)}{[1,457.5 - h_{min}]}$ is an area scaling factor.

The parameters a, b, and c were fitted to known areas of each bay (table A1) using nonlinear least-squares regression. The minimum (dry lakebed) elevation of each bay was approximated by examining contour maps of the lakebed. The fitted parameter values are given in table A2, and calculated and known areas are shown in figure A1. The agreement was deemed satisfactory for each box. Tables of areas and volumes for 1-foot increments are given in appendix B.

Table A2. Fitted parameters for elevation/area equations for lake boxes

Box	h_{min}	a	b	c	A_s
West Bay North	1,430	1.25	0.65	1.79	120,800
West Bay South	1,415	.78	.58	1.25	37,000
Main Bay	1,398	1.09	-.22	.59	32,500
East Bay	1,405	1.02	-.47	.77	34,750
East Devils Lake	1,387	1.22	-.18	.67	9,000
Stump Lake	1,380	1.26	-.08	.83	22,000

Water Mass-Balance Computations

Given the water mass-balance equations (eqs. 4 through 9), starting volumes $[V_i(t-1)]$ and areas $[A_i(t-1)]$ for each of the lake boxes, and values of precipitation $[P(t)]$, evaporation $[E(t)]$, inflow from Big Coulee $[Q_B(t)]$, inflow from Channel A $[Q_A(t)]$, and ungaged inflow $[U(t)]$, the only undetermined quantities were local inflow to Stump Lake $[Q_S(t)]$, the fluxes between boxes [the $Q_{ij}(t)$'s], and the natural outlet flow $[Q_N(t)]$. These quantities were determined as described in this section.

Inflow to Stump Lake

Local inflow to Stump Lake was estimated indirectly using sporadic lake-level measurements. Two lake-level measurements per year are available for 1956-79 (from North Dakota State Water Commission and Nelson County records), and four lake-level measurements per year are available for 1994-99 (from USGS records). Daily lake levels are available from gaging station 05056665 (Eastern Stump Lake near Lakota, N. Dak.) beginning with water year 2000.

From 1956 to 1979, Stump Lake consisted of two separate water bodies--East Stump Lake and West Stump Lake. The level of East Stump Lake ranged from a low of 1,381.6 feet above sea level in 1964 to a high of 1,385.4 feet above sea level in 1974. The level of West Stump Lake ranged from a low of 1,394.6 feet above sea level in 1960 to a high of 1,399.9 feet above sea level in 1972. From 1956 to 1964, a very dry period, the level of East Stump Lake remained nearly constant at about 1,383 feet above sea level, the level of West Stump Lake remained nearly constant at about 1,395 feet above sea level, and the combined surface area of the two lakes remained nearly constant at about 2,800 acres. During the same time, the level of Devils Lake dropped about 9 feet (fig. 3). The relatively stable lake levels for Stump Lake during 1956-64 probably indicate that ground-water inflow was a significant component of the water balance during that period. Assuming average annual net evaporation for 1956-64 was about 10.1 inches (the same as for Devils Lake; table 13), ground-water inflow of about 2,400 acre-feet per year would be required to maintain constant lake levels. Therefore, ground-water inflow of 200 acre-feet per month was assumed in the water balance for Stump Lake.

During wet periods, the water balance of Stump Lake is significantly affected by surface inflow. Stump Lake received significant surface inflow during 1993 and 1994 and, at the end of 1994, the level of Stump Lake was 1,398 feet above sea level. From 1995

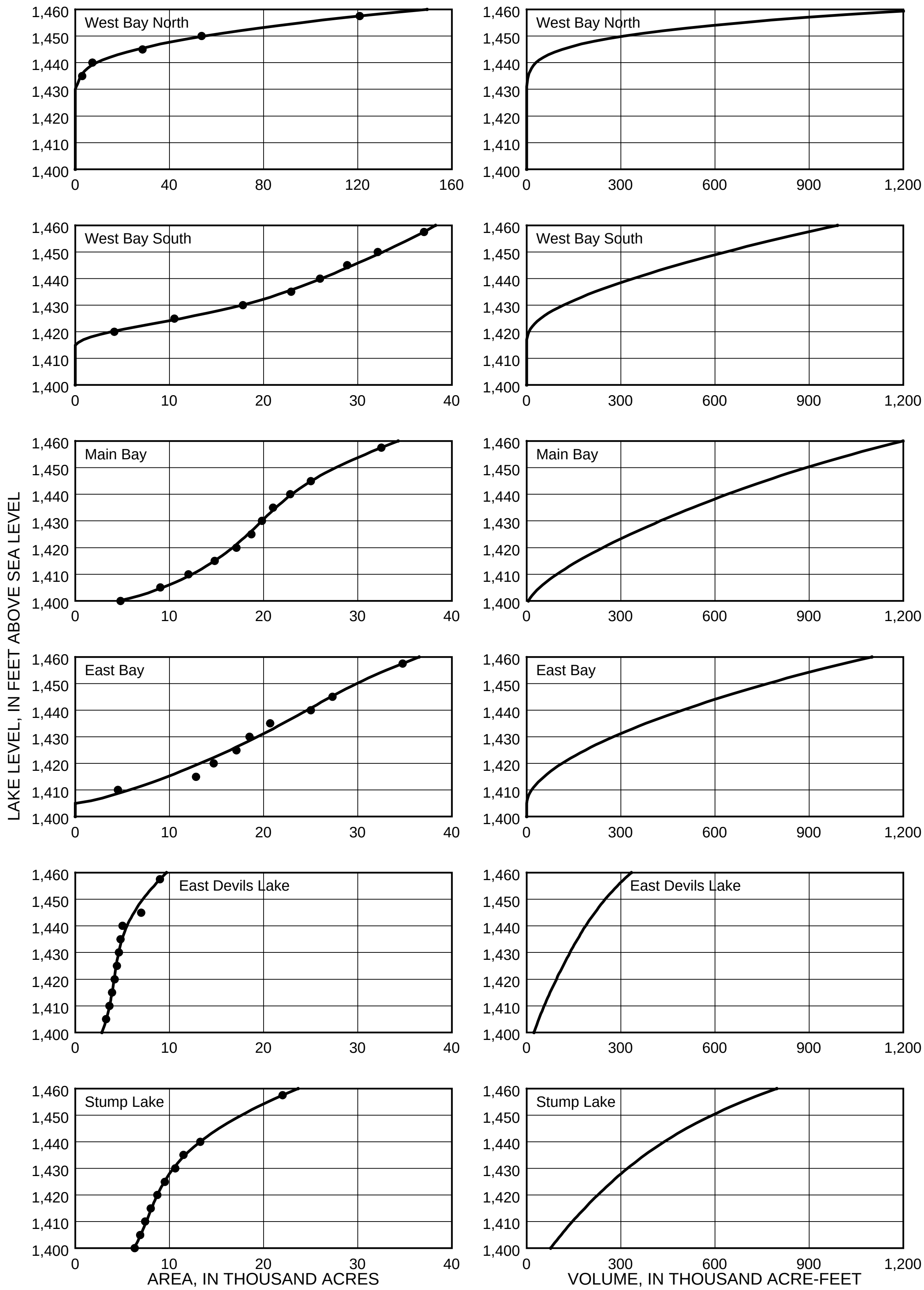

Figure A1. Elevation-area and elevation-volume relations for Devils Lake and Stump Lake. (Points indicate known areas, and lines indicate fitted equations.)

through 1999, the lake level rose from 1,398 feet above sea level to about 1,408 feet above sea level (fig. A2). In the water mass-balance model, local inflow to Stump Lake for a particular month was estimated by adding 42 percent of estimated ungaged inflow for Devils Lake to the estimated monthly ground-water inflow of 200 acre-feet:

$$Q_S(t) = 200 + 0.42U(t).$$

The multiplier of 0.42 for $U(t)$ was obtained by requiring the estimated lake levels (fig. A2) at the beginning of 1995 and at the end of 1999 to agree with the recorded lake levels of Stump Lake (fig. A2). Although the recorded and estimated lake levels shown in figure A2 differ by almost 2 feet in 1996 and 1997, the difference between recorded and estimated volumes in those years is only about 15,000 acre-feet. The volume of Stump Lake increased by about 68,000 acre-feet from the beginning of 1995 to the end of 1999 (from about 64,000 acre-feet to about 132,000 acre-feet). During that same time, the volume of Devils Lake increased by about 1.4 million acre-feet. Thus, errors in the water balance for Stump Lake should not have a significant effect on computed lake levels for Devils Lake.

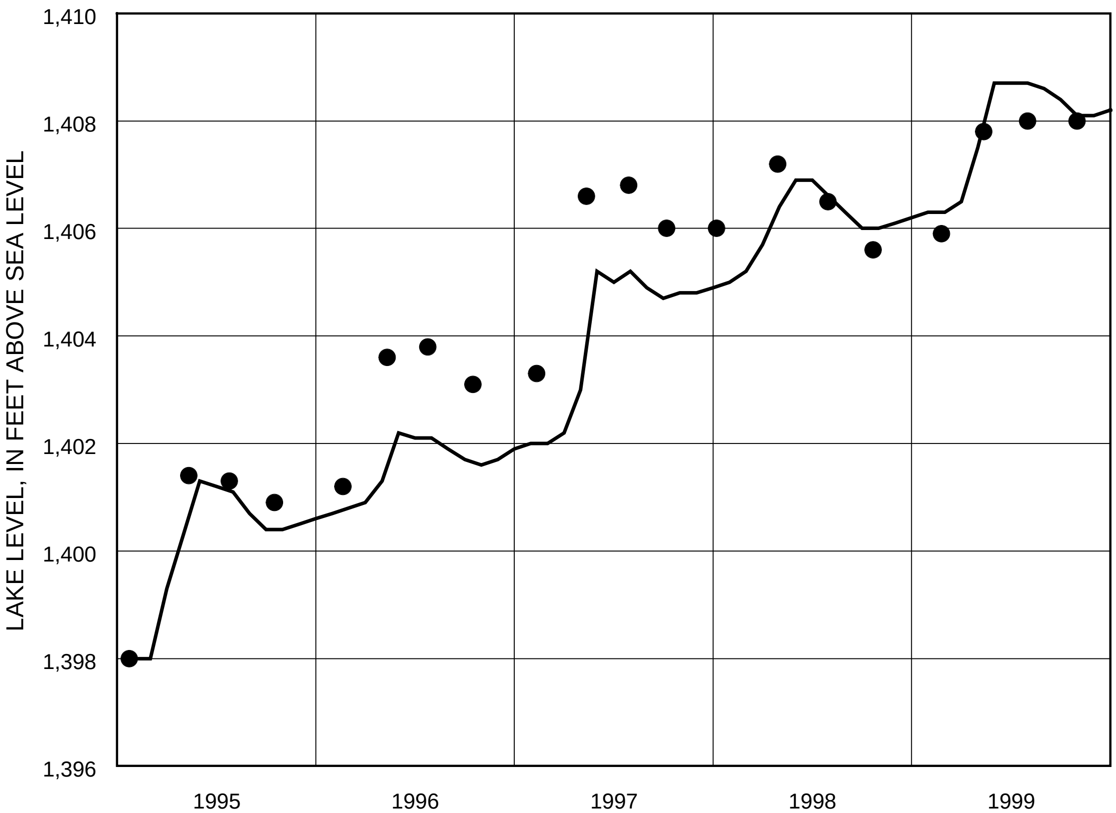

Figure A2. Recorded and estimated lake levels of Stump Lake for 1995-99. (Points indicate recorded lake levels, and line indicates estimated lake level.)

Flows Between Lake Boxes

To compute flows between lake boxes, the lake boxes were assumed to be in upstream to downstream order. Thus, flow from West Bay North (box 0) to West Bay South (box 1) was computed first so either box 0 was empty or box 0 and box 1 had the same level. Then, flow from West Bay South to Main Bay (box 2) was computed so either box 1 was empty or box 1 and box 2 had the same level. If box 0 and box 1 were joined and flow occurred between box 1 and box 2, additional flows were computed between box 0 and box 1 to maintain a constant lake level between those boxes. Then, if Main Bay was above its spill elevation with East Bay (box 3), flow between box 2 and box 3 was computed so either box 2 was reduced to its spill elevation and box 3 was below the spill elevation for box 2 or box 2 and box 3 were both above the spill elevation for box 2. If box 2 and box 3 were both above the spill elevation for box 2, the flow from box 2 to box 3 was computed so the levels of box 2 and box 3 were the same. If flow occurred between box 2 and box 3, additional flows were computed between box 0 and box 1 and between box 1 and box 2. Then, flows between East Bay and East Devils Lake (box 4) were computed in a similar manner, and additional flows were computed between boxes 0 through 3 if necessary. If East Devils Lake was above its spill elevation to Stump Lake (box 5), flow from box 4 to box 5 was computed using a flow rating described later. If spills from East Devils Lake caused the level of Stump Lake to rise above the spill elevation of East Devils Lake (1,446.5 feet above sea level), the spill rating was modified for backwater from Stump Lake until the levels of Devils Lake and Stump Lake were within 0.1 foot, after which Stump Lake was joined with Devils Lake. After Stump Lake was joined with Devils Lake, flow between box 4 and box 5 was computed so the levels of those boxes were the same. If the combined Devils Lake and Stump Lake system was above the spill elevation of Stump Lake (1,459 feet above sea level), flow from Stump Lake to Tolna Coulee was computed using the flow rating described later. The methods for computing flows between lake boxes are more thoroughly described in the following algorithm.

Some preliminary notation is helpful for simplifying the algorithm for computing flows between lake boxes. The dependence on t (the month) in equations 4 through 9 is not indicated in the algorithm. Rather, the volume of the ith lake box at the end of the previous month is denoted by

$$V0(i) = V_i(t-1)$$

and the volume of the ith lake box at the end of the current month is denoted by

$$V(i) = V_i(t) .$$

The volume of the ith lake box corresponding to a fixed lake level is denoted by

$V^*(i; h)$ = the volume of lake box i, in acre-feet, corresponding to lake level h, in feet above sea level.

$V^*(i; h)$ was computed using the modified equation for lake volume with the appropriate parameters from table A2. Volume is a strictly increasing function of h and, therefore, can be numerically inverted to compute the lake level corresponding to a given lake-box volume,

$L^*(i; \mathrm{v})$ = the level of lake box i, in feet above sea level, corresponding to a given lake-box volume, v, in acre-feet.

The total volume of Devils Lake (excluding Stump Lake) at the end of the previous month is denoted by

$$V0(DL) = V0(0) + V0(1) + \ldots + V0(4)$$

and the total volume of Devils Lake at the end of the current month is denoted by

$$V(DL) = V(0) + V(1) + \ldots + V(4) .$$

The total volume of Devils Lake for a given lake level is denoted by

$$V^*(DL; h) = V^*(0; h) + V^*(1; h) + \ldots + V^*(4; h)$$

and the lake level of Devils Lake for a given total volume is denoted by

$$L^*(DL; v) .$$

Algorithm Used to Compute Flows Between Lake Boxes

1. Start with no outflow from any of the lake boxes:

$$Q_{01} = Q_{12} = Q_{23} = Q_{34} = Q_{45} = Q_N = 0$$

2. Calculate volumes for each lake box $[V(0), \ldots V(5)]$ using equations 4 through 9. The resulting volumes account for gaged and ungaged inflow, precipitation, and evaporation for the current time step.

3. If an outlet is discharging from one of the lake boxes, remove outlet discharge (Q_P, eq. 39) from the appropriate lake box.

4. Calculate flow from West Bay North to West Bay South:
   If $[V(0) + V(1) - Q_{12} < V^*(1; 1{,}430)]$, set $Q_{01} = V(0)$ and proceed to step 5.
   Otherwise, compute Q_{01} such that $L^*[0; V(0) - Q_{01}] = L^*[1; V(1) + Q_{01} - Q_{12}]$ and proceed to step 5.

5. Calculate flow from West Bay South to Main Bay:
   If $[V(1) + V(2) + Q_{01} - Q_{23} < V^*(2; 1{,}415)]$, set $Q_{12} = V(1) + Q_{01}$ and proceed to step 6.
   Otherwise, compute Q_{12} such that $L^*[1; V(1) + Q_{01} - Q_{12}] = L^*[2; V(2) + Q_{12} - Q_{23}]$ and proceed to step 6.

6. Repeat steps 4 and 5 until the levels of lake boxes 0, 1, and 2 stabilize. The levels stabilize if any of the following conditions are met:
   a. The level of box 2 is less than 1,415 feet above sea level and boxes 0 and 1 are empty.
   b. The level of box 2 is between 1,415 and 1,430 feet above sea level, box 0 is empty, and the difference in levels between box 1 and box 2 is less than 0.05 foot.
   c. The level of box 2 is greater than 1,430 feet above sea level and the differences in levels between boxes 0, 1 and 2 are less than 0.05 foot.

7. Compute flow from Main Bay to East Bay ($E23$ is the minimum elevation of the connection between Main Bay and East Bay as determined by the appropriate bridge opening from table 4):
   If $[V(2) + Q_{12} - Q_{23} < V^*(2; E23)$ and $V(3) + Q_{23} - Q_{34} < V^*(3; E23)]$, leave Q_{23} unchanged and proceed to step 8.
   Otherwise, if $[V(2) + Q_{12} - Q_{23} > V^*(2; E23)$ and $V(2) + V(3) + Q_{12} - Q_{34} < V^*(2; E23) + V^*(3; E23)]$, set $Q_{23} = V(2) + Q_{12} - V^*(2; E23)$ and proceed to step 8.
   Otherwise, if $[V(3) + Q_{23} - Q_{34} > V^*(3; E23)$ and $V(2) + V(3) + Q_{12} - Q_{34} < V^*(2; E23) + V^*(3; E23)]$, set $Q_{23} = V^*(3; E23) - V(3) + Q_{34}$ and proceed to step 8.
   Otherwise, compute Q_{23} such that $L^*[2; V(2) + Q_{12} - Q_{23}] = L^*[3; V(3) + Q_{23} - Q_{34}]$ and proceed to step 8.

8. Repeat steps 4 through 7 until the levels of lake boxes 0 through 3 stabilize. The levels stabilize if, in addition to satisfying step 6, either of the following conditions are met:
   a. The levels of boxes 2 and 3 are at or below $E23$.
   b. The difference in levels between box 2 and box 3 is less than 0.05 foot.

9. Compute flow from East Bay to East Devils Lake ($E34$ is the minimum elevation of the connection between East Bay and East Devils Lake as determined from table 4):
   If $[V(3) + Q_{23} - Q_{34} < V^*(3; E34)$ and $V(4) + Q_{34} - Q_{45} < V^*(4; E34)]$, leave Q_{34} unchanged and proceed to step 10.
   Otherwise, if $[V(3) + Q_{23} - Q_{34} > V^*(3; E34)$ and $V(3) + V(4) + Q_{23} - Q_{45} < V^*(3; E34) + V^*(4; E34)]$, set $Q_{34} = V(3) + Q_{23} - V^*(3; E34)$ and proceed to step 10.
   Otherwise, if $[V(4) + Q_{34} - Q_{45} > V^*(4; E34)$ and $V(3) + V(4) + Q_{23} - Q_{45} < V^*(3; E34) + V^*(4; E34)]$, set $Q_{34} = V^*(4; E34) - V(4) + Q_{45}$ and proceed to step 10.
   Otherwise, compute Q_{34} such that $L^*[3; V(3) + Q_{23} - Q_{34}] = L^*[4; V(4) + Q_{34} - Q_{45}]$ and proceed to step 10.

10. Repeat steps 4 through 9 until the levels of lake boxes 0 through 4 stabilize. The levels stabilize if, in addition to satisfying steps 6 and 8, either of the following conditions are met:
    a. The levels of boxes 3 and 4 are at or below $E34$.
    b. The difference in levels between box 3 and box 4 is less than 0.05 foot.

11. Check for potential flow between East Devils Lake and Stump Lake ($E45$ is the minimum elevation of the connection between East Devils Lake and Stump Lake, which is 1,446.5 feet above sea level for the existing connection):
    If $[V(DL) < V^*(DL; E45)$ and $V(5) < V^*(5; E45)]$, set $Q_{45} = 0$ and $Q_N = 0$ and proceed to step 19. Otherwise, proceed to step 12.

12. Compute flow between East Devils Lake and Stump Lake for the case when East Devils Lake is above $E45$ and Stump Lake is below $E45$ (spill rating required):
    If $[V(DL) > V^*(DL; E45)$ and $V(5) < V^*(5; E45)]$, compute Q_{45} as described in the remainder of step 12. Otherwise, proceed to step 13.
    The North Dakota State Water Commission (James Landenberger, written commun., June 2001) used hydraulic modeling to estimate the lake stage-discharge rating for flow from East Devils Lake to Stump Lake for the case when Devils Lake is above $E45$ and Stump Lake is below $E45$. The rating curve was approximated closely by

$$Q_D(L) = 100[L - E45]^2$$

where

$Q_D(L)$ is discharge, in acre-feet per day; and

$L > E45$ is the level of Devils Lake, in feet above sea level.

Let $V(DL) - V0(DL)$ be the total increase (if positive) or decrease (if negative) in volume of Devils Lake from the previous time step to the current time step. Assuming the volume increase (or decrease) occurs uniformly for 30 (approximately daily) subintervals, the sum of the daily discharges from Devils Lake to Stump Lake for the first J subintervals can be approximated as follows:

$$S(J) = S(J-1) + Q_D\left(L^*\left[DL;\ V0(DL) + (J-1)\frac{[V(DL) - V0(DL)]}{30} - S(J-1)\right]\right)$$

where

$S(J)$ is the sum of the daily discharges for days $1, 2, \ldots, J[S(0) = 0]$.

If $V(5) + S(30)$ is less than $V^*(5;\ E45)$, set $Q_{45} = S(30)$ and proceed to step 15. Otherwise, leave Q_{45} unchanged and proceed to step 13.

13. Compute flow from East Devils Lake to Stump Lake for the case when Stump Lake is above $E45$ (no spill rating required):
    If $[V(DL) + V(5) < V^*(DL;\ E45) + V^*(5;\ E45)]$, set $Q_{45} = V^*(5;\ E45) - V(5)$ and proceed to step 14.
    Otherwise, compute Q_{45} such that $L^*[DL;\ V(DL) - Q_{45}] = L^*[5;\ V(5) + Q_{45}]$ and proceed to step 14.

14. Repeat steps 4 through 10 and 13 until the levels of lake boxes 0 through 5 stabilize. The levels stabilize if, in addition to satisfying steps 6, 8, and 10, either of the following conditions are met:
    a. The level of boxes 4 and 5 are at or below $E45$.
    b. The difference in levels between box 4 and box 5 is less than 0.05 foot.
    After the levels of boxes 0 through 5 stabilize, proceed to step 16.

15. Repeat steps 4 through 9 until the levels of lake boxes 0 through 4 stabilize. No additional flow is allowed from East Devils Lake to Stump Lake other than the flow calculated in step 12. After the levels stabilize, proceed to step 19.

16. Check for potential flow from Stump Lake to the Sheyenne River ($E5$ is the spill elevation of Stump Lake, which is 1,459.0 feet above sea level under existing conditions):
    If $V(5) < V^*(5;\ E5)$, set $Q_N = 0$ and proceed to step 19. Otherwise, proceed to step 17.

17. Compute monthly discharge from Stump Lake to Tolna Coulee (spill rating required):
    The following approximate stage-discharge rating for Stump Lake was developed on the basis of hydraulic analyses provided by the Corps (Patrick Foley, written commun., June 2001) (see next section for more details):

$$Q_{ND}(L) = 310(L - E5)^2$$

where

Q_{ND} is discharge from Stump Lake, in acre-feet per day; and

$L > E5$ is the level of Stump Lake, in feet above sea level.

The total discharge from Stump Lake for the first J days of the month is approximated by

$$SN(J) = SN(J-1) + Q_{ND}\left(L^*\left[VTOT0 + (J-1)\frac{[VTOT - VTOT0]}{K} - SN(J-1)\right]\right)$$

where

$VTOT0 = V0(DL) + V0(5)$;

$VTOT = V(DL) + V(5)$;

K is the number of days in the current month;

$L^*(v)$ is the level of the combined Devils Lake and Stump Lake system for fixed total volume, v; and

$SN(0) = 0$.

Set $Q_N = SN(K)$ and proceed to step 18.

18. Repeat steps 4 through 9 and 13 until the levels of lake boxes 0 through 5 stabilize. After the levels stabilize, proceed to step 19.

19. Compute new volumes of the lake boxes at the end of the current month using equations 4 through 9. The resulting values account for all inflow and outflow, precipitation, and evaporation for the current month. Set $V0(i) = V(i)$ for $i = 0, ..., 5$, increment to the next month, and proceed to step 1.

Erosion of Natural Outlet from Stump Lake

A profile of the channel thalweg for the upper reach of Tolna Coulee is shown in figure A3 (Alan Fandrey, Barr Engineering, written commun., 2001). The divide between Stump Lake and Tolna Coulee is at a distance of about 75,000 feet (14.2 miles) from the confluence of Tolna Coulee and the Sheyenne River. A berm of unknown origin exists about 2,000 feet downstream of the divide. The berm has an elevation of about 1,459 feet above sea level. The stage-discharge relation for the existing channel is shown by the upper curve in figure A4. The points along the curve are estimated values obtained from the Corps (Patrick Foley, oral commun., 2000). The curve is given by the following equation:

$$Q = 157(L - 1{,}459)^2$$

where

Q is discharge, in cubic feet per second; and

$L > 1{,}459$ is the level of Stump Lake, in feet above sea level.

Full evaluation of the erosion process for Tolna Coulee would require detailed hydraulic and geomorphologic analyses that are beyond the scope of this study. The erosion analysis described here is based on a preliminary study by Barr Engineering (Alan Fandrey, written commun., 2001).

As water begins to spill from Stump Lake, the berm near the divide would begin to erode, but the elevation of the divide would remain at 1,459 feet above sea level. After about 16,000 cubic yards of sediment are eroded from the berm, the stage-discharge relation would change from the existing relation to the following relation (fig. A4, second curve):

$$Q = 276(L - 1{,}459)^{1.67}.$$

If erosion continues, the divide would begin to erode below 1,459 feet above sea level. The stage-discharge relation would change depending on the amount of erosion. The dependence of the stage-discharge relation on erosion volume can be approximated by

$$Q = (276 - 0.53Y)[L - h(Y)]^{1.67} \text{ for } L > h(Y) \text{ and } 0 < Y < 162$$

where

$$Y = \frac{(W - 16{,}000)}{1{,}000};$$

W is the erosion volume, in cubic yards; and

$h(Y) = 1{,}459 - 0.155Y^{0.78}$ is the elevation of the divide, in feet above sea level.

The stage-discharge relations that correspond to erosion volumes W = 16,000 ($Y = 0$), W = 41,000 ($Y = 25$), W = 96,000 ($Y = 80$), and W = 178,000 ($Y = 162$) are shown in figure A4. If erosion continues beyond 178,000 cubic yards, the elevation of the divide would remain at 1,450.8 feet above sea level, but erosion would continue downstream of the divide, increasing flow velocities until an ultimate equilibrium is reached at an erosion volume of about 937,000 cubic yards (fig. A3). The stage-discharge relation for erosion

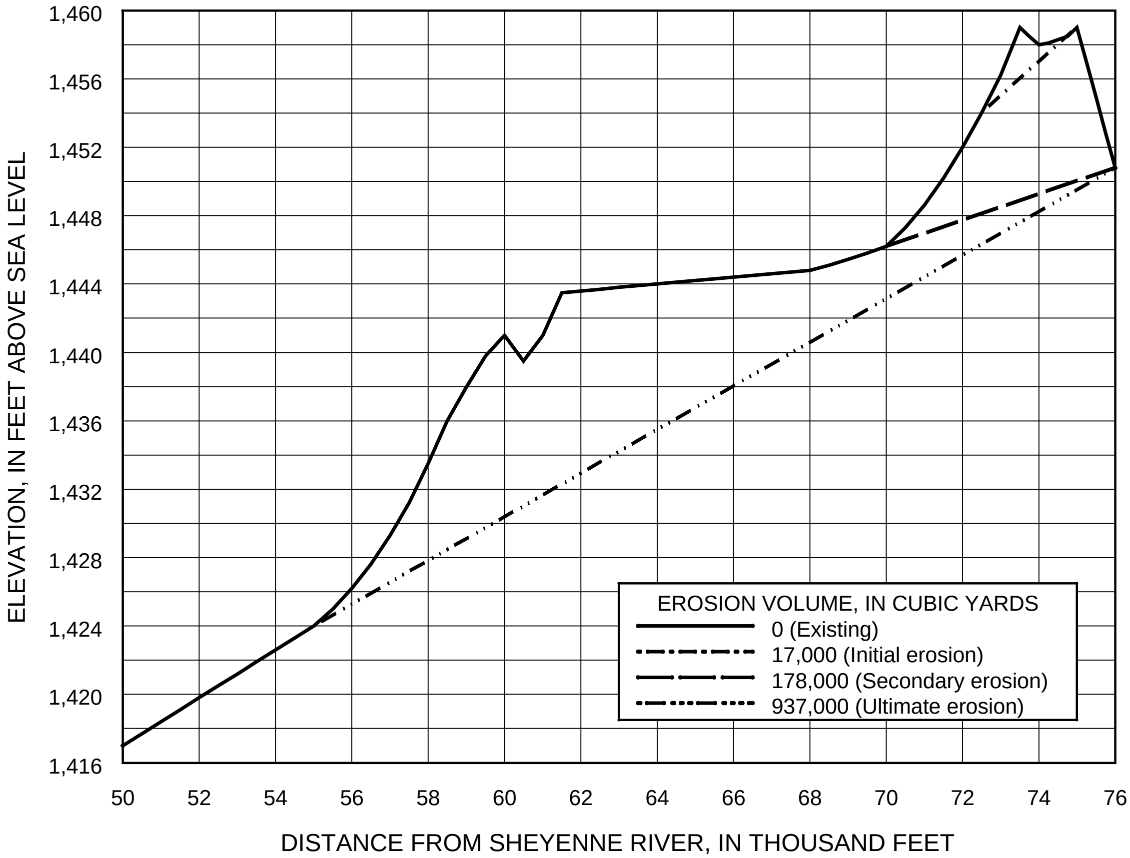

Figure A3. Profiles of Tolna Coulee channel thalweg for existing and eroded conditions.

volumes greater than 178,000 cubic yards is approximated by

$$Q = [190 + 0.066(Y - 162)](L - 1{,}450.8)^{1.67} \text{ for } L > 1{,}450.8 \text{ and } 162 < Y < 921 \text{; and}$$

$$Q = 240(L - 1{,}450.8)^{1.67} \text{ for } L > 1{,}450.8 \text{ and } Y > 921 \text{ .}$$

The ultimate erosion relation ($W = 937{,}000$ or $Y = 921$) is shown in figure A4. Further erosion of the Tolna Coulee channel may occur after the ultimate erosion relation is reached, but the erosion is likely to occur well downstream of the divide and, thus, the stage-discharge relation at the divide would not change substantially.

The previous stage-discharge relations can be used to approximate discharge for given erosion volumes. However, they cannot be used to determine the erosion rate. The erosion rate depends on the time series of daily Tolna Coulee discharges and suspended-sediment concentrations downstream of the erosion reach. The time series of daily discharges can be computed as described in the previous algorithm. However, the suspended-sediment concentrations of the daily discharges are subject to a high degree of uncertainty. Suspended-sediment concentrations depend on the particle size of the underlying soils, the flow velocities, and the channel geometry, all of which may change as the erosion progresses. The suspended-sediment concentration of Stump Lake outflow at the divide is likely to be small and independent of the flow rate, and the suspended-sediment load should consist primarily of fine silts. Thus, most of the suspended-sediment load downstream of the erosion reach is likely to be from channel erosion. For a fixed discharge, the “sediment-starved” water from Stump Lake likely would reach an equilibrium concentration within several miles downstream, after which sediment concentrations would remain relatively constant from that point downstream to the Sheyenne River. The relation between the equilibrium concentration and discharge can be used along with the time series of daily discharges to approximate the erosion rate in the upper reach of Tolna Coulee. Unfortunately, no data are available for directly estimating the relation between equilibrium sediment concentration and discharge for Tolna Coulee. Therefore, suspended-sediment data from other streams in eastern North Dakota will be used as a surrogate for data for Tolna Coulee.

Soils in the Sheyenne River Basin (including Tolna Coulee) are fairly homogeneous and consist of a sandy loam that is easily eroded. Soil profiles from the Stump Lake-Tolna Coulee divide (Murphy and others, 1997) indicate no erosion-resistant materials

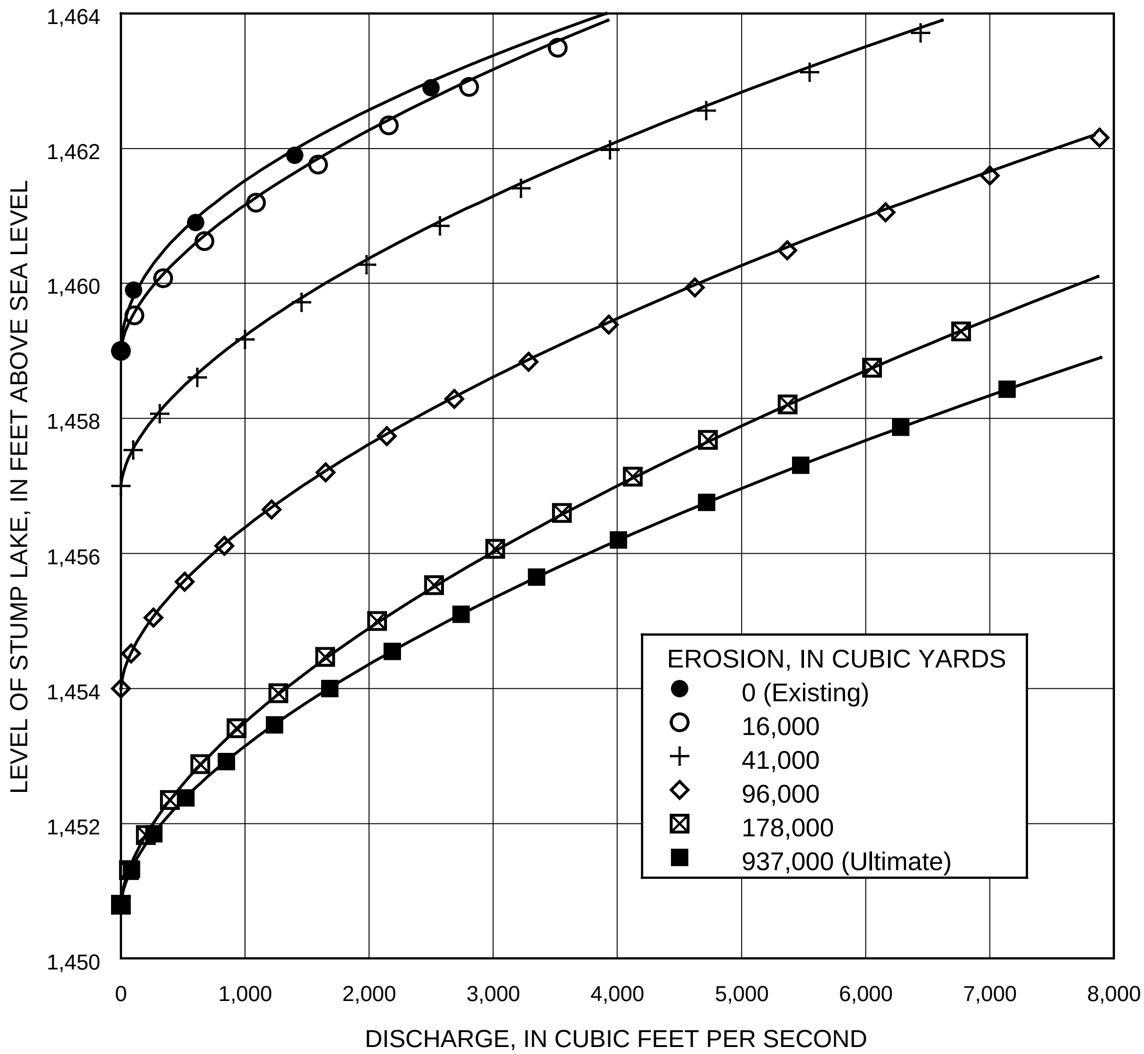

Figure A4. Rating curves for discharge from Stump Lake under existing and eroded conditions.

within the 20-foot sampling depth; therefore, there probably would not be any natural barrier to prevent erosion. Thus, suspended-sediment concentrations downstream of the divide should increase rapidly as flow velocity increases and fine particles become suspended. Channel slopes (and flow velocities) in the upper reach of Tolna Coulee are higher than slopes (and velocities) typical of the main stem of the Sheyenne River. Therefore, suspended-sediment concentrations in Tolna Coulee probably would be higher (for a given discharge) than suspended-sediment concentrations in the Sheyenne River. The relation between suspended-sediment concentration and discharge for the Sheyenne River at Lisbon and Kindred, N. Dak., is shown in figure A5. The points in figure A5 are recorded values for 1974-95, and the line is the ordinary least-squares line fitted to the recorded data:

$$\log (C) = 0.88 + 0.48 \log (Q)$$

where

C is the suspended-sediment concentration, in milligrams per liter; and

Q is discharge, in cubic feet per second.

Using a density of 2.65 grams per milliliter for the sediment and converting this equation to daily sediment load yields

$$S_D = 0.00883 Q_D^{1.48}$$

where

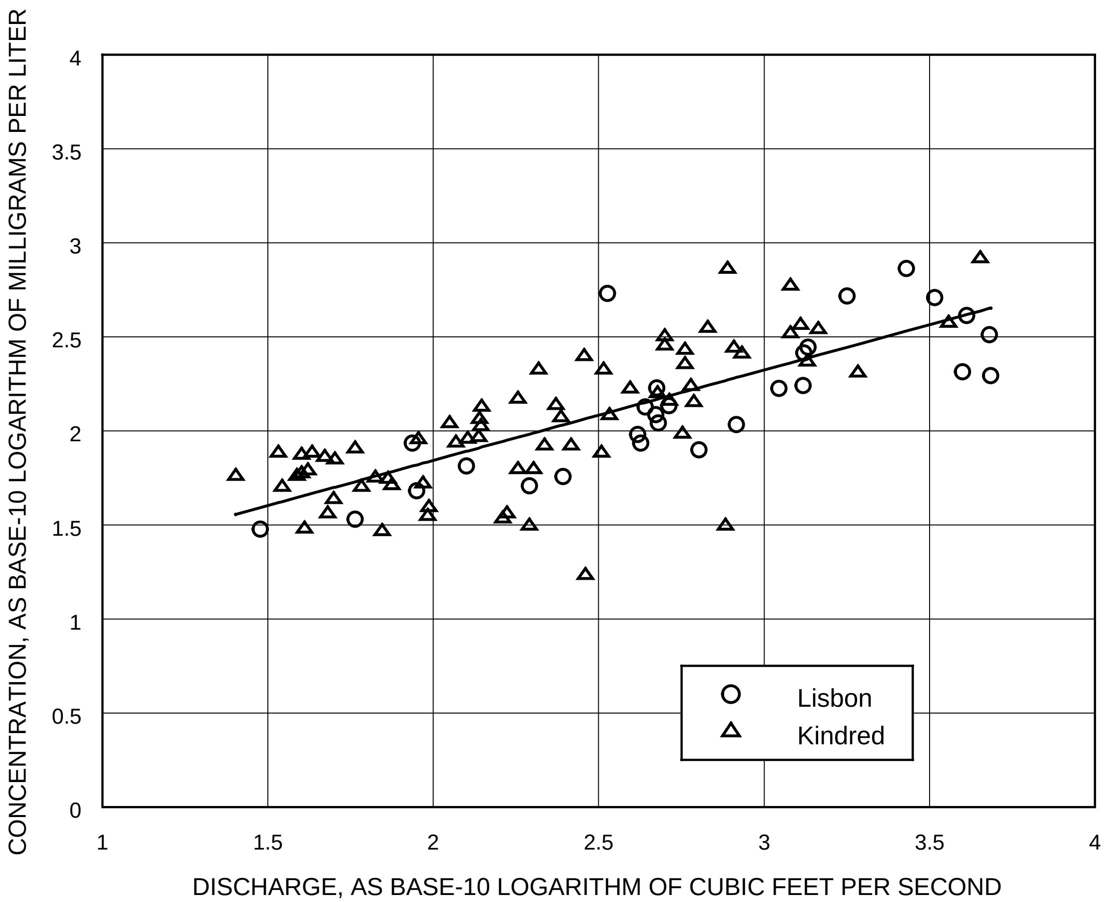

Figure A5. Suspended-sediment concentrations and discharges for the Sheyenne River at Lisbon, North Dakota, and the Sheyenne River at Kindred, North Dakota, for 1974-95. (Points indicate recorded values, and line indicates fitted value.)

S_D is the sediment load, in cubic yards per day; and

Q_D is discharge, in acre-feet per day.

In the erosion analysis for the wet scenario, the cumulative erosion volume from the start of the simulation period to day T of the simulation period was calculated by summing the daily sediment loads for the first T days:

$$W(T) = S_{D1} + \ldots + S_{DT}$$

where

$W(T)$ is the total erosion volume from day 1 to day T, in cubic yards, and

$$S_{Dj} = 0.00883 Q_{Dj}^{1.48}$$

where

Q_{Dj} is discharge from Stump Lake for the jth day of the simulation period, in acre-feet.

The total erosion volume $W(T)$ was used to adjust the stage-discharge relation for day $T + 1$ using the previous stage-discharge equations with $W = W(T)$, and the adjusted relation was used in step 17 of the algorithm to compute flows between lake boxes to compute the Stump Lake discharge for day $T + 1$. The actual erosion probably will occur faster than the erosion calculated using this procedure, assuming sediment concentrations calculated using the Sheyenne River data underestimate the actual sediment concentrations in Tolna Coulee.

Calculation of Ambient Sheyenne River Streamflow for Outlet Simulations

The outlet simulation model requires ambient (without-outlet) daily streamflows for the Sheyenne River for the outlet simulation period (water years 2001-50). The streamflows needed to be "in phase" with Devils Lake precipitation, evaporation, and inflow and needed to be expressed in terms of recorded streamflows to be compatible with the Corps' HEC-5Q computer model. This section describes the procedure used to calculate daily streamflows for the Sheyenne River.

Seasonal Sheyenne River streamflows first were generated in concert with the seasonal precipitation, evaporation, and inflow data for Devils Lake. The time-series model used to generate the seasonal Sheyenne River streamflows is given in table A3. The equations used to generate the transformed variables were developed using the same methods described previously for developing the equations to generate transformed Devils Lake precipitation, evaporation, and inflow (see table 10 and related discussion). Potential explanatory variables for transformed Sheyenne River streamflow included concurrent and antecedent values of transformed Devils Lake precipitation, evaporation, and gaged inflow and antecedent values of transformed Sheyenne River streamflow. The model was verified using techniques similar to the time-series model verification techniques for Devils Lake inputs, and the generated seasonal Sheyenne River streamflows were determined to provide a good representation of the statistical properties of recorded Sheyenne River streamflows, including the cross correlations between Sheyenne River streamflows and Devils Lake inputs. The winter $(OCT - MAR)$ streamflows were disaggregated into the separate months using methods similar to those described previously for the Devils Lake inputs.

Table A3. Fitted time-series model used to generate seasonal streamflows for the Sheyenne River near Warwick

[See table 10 for definition of transformed variables related to Devils Lake precipitation, evaporation, and gaged inflow]

Season	Transformed variable[1]	Equation for generating transformed variable for jth water year[2]	Coefficient of determination (percent)
$OCT - MAR$	$WWIN = (\log W - 4.08)/0.51$	$WWIN(j) = 0.54GWIN(j) + 0.49PWIN(j) + 0.58Z$	78
APR	$WAPR = (\log W - 4.07)/0.57$	$WAPR(j) = 0.80GAPR(j) + 0.30PAPR(j) + 0.56Z$	72
MAY	$WMAY = (\log W - 3.65)/0.48$	$WMAY(j) = 0.83WAPR(j) + 0.52Z$	73
JUN	$WJUN = (\log W - 3.34)/0.46$	$WJUN(j) = 0.82WMAY(j) + 0.57PJUN(j) + 0.53Z$	75
JUL	$WJUL = (\log W - 3.11)/0.81$	$WJUL(j) = 0.63WJUN(j) + 0.35[PJUL(j) - EJUL(j)] + 0.46Z$	82
AUG	$WAUG = (\log W - 2.94)/0.81$	$WAUG(j) = 0.74WJUL(j) + 0.21[PAUG(j) - EAUG(j)] + 0.42Z$	84
SEP	$WSEP = (\log W - 2.81)/0.59$	$WSEP(j) = 0.91WAUG(j) + 0.29PAUG(j) + 0.31Z$	91

[1] W is streamflow, in acre-feet, for the Sheyenne River near Warwick, N. Dak.

[2] Z is a standard normal random variable that is generated independently for each season.

The monthly Sheyenne River streamflows generated using the time-series model were not expressed in terms of recorded streamflows. Thus, a procedure was required to make the generated data compatible with the Corps' downstream water-quality models. For each 50-year trace generated from the outlet simulation model, the Corps' model was configured to accept a sequence of historical water years selected from among water years 1971-99. For example, the wet scenario described previously consisted of one particular sequence of historical water years that were repeated in the future. However, when considering the entire set of 10,000 stochastic traces from the outlet simulation model, Sheyenne River streamflows well outside of the range of recorded values for 1971-99 often were generated. Therefore, the Corps' model also was configured to accept a sequence of multipliers along with the sequence of water years. For example, the first year of a particular trace might consist of repeating recorded data for water year 1999 (which was the year with the highest annual streamflow for the Sheyenne River), multiplied by 1.2. Thus, in the Corps' model, each of the daily streamflows for 1999 were increased 20 percent. Streamflows were increased, not only at the outlet insertion point, but at every other downstream node for which incremental streamflows were required as well. The next year of the trace might consist of repeating recorded flows for 1979, multiplied by 0.8, and so on.

Each of the 10,000 traces of Sheyenne River streamflows generated from the statistical time-series model was reconfigured to correspond with a particular sequence of historical water years and multipliers. Several methods were tried to reconfigure the traces--

only the method that worked best (that is, produced the most realistic traces) is described here. For each simulation year, a measure of the difference between the monthly Sheyenne River streamflows generated from the time-series model and the recorded monthly streamflows was computed:

$$D(k) = \mathrm{sum}_j\{\mathrm{abs}[W_G(j) - W_H(j;\ k)]\}$$

where

$D(k)$ is a measure of the difference between generated monthly streamflows and recorded monthly streamflows for water year k ($k = 1971, 1972, \ldots, 1999$);

$W_G(j)$ is the generated Sheyenne River streamflow for month j of the simulation year ($j = 1, \ldots, 12$), in acre-feet;

$W_H(j;\ k)$ is the recorded Sheyenne River streamflow for month j of year k, in acre-feet;

sum_j denotes the sum over all months of the simulation year; and

abs denotes the absolute value.

An historical water year, k^*, then was selected such that $D(k^*)$ was equal to the minimum of $D(k)$ over all historical water years. The multiplier for the selected historical year was equal to the ratio between generated annual streamflow for the simulation year and annual streamflow for the historical year:

$$R = \frac{\mathrm{sum}_j\{W_G(j)\}}{\mathrm{sum}_j\{W_H(j;\ k^*)\}}.$$

Generated daily streamflows for the simulation year were computed by multiplying recorded daily streamflows for year k^* by the ratio R.

APPENDIX B

Table B1. Monthly water-balance data for Devils Lake for 1980-99

[Precipitation, evaporation, and ungaged inflow were estimated using a water-balance model described in this report, and values may not agree with published estimates from earlier studies]

Year	Month	Precipitation (inches)	Evaporation (inches)	Inflow from Big Coulee (acre-feet)	Inflow from Channel A (acre-feet)	Ungaged inflow (acre-feet)
1980	January	0.74	0	12.0	0	0.2
1980	February	.61	0	0	0	0
1980	March	.52	0	25.0	12.5	35.0
1980	April	.61	.45	1,200.0	1,800.0	349.8
1980	May	1.26	4.18	379.0	379.0	141.4
1980	June	3.13	6.10	45.0	22.5	1.2
1980	July	3.98	7.05	.1	0	0
1980	August	4.73	5.34	76.0	0	1.3
1980	September	3.88	3.70	159.0	0	2.7
1980	October	2.01	2.18	113.0	0	1.9
1980	November	.94	1.58	124.0	0	2.1
1980	December	.38	0	28.0	0	.5
1981	January	.54	0	0	0	0
1981	February	1.57	0	217.0	0	3.7
1981	March	.51	0	1,520.0	760.0	2,130.0
1981	April	1.86	2.10	4,760.0	7,140.0	1,387.7
1981	May	1.34	3.50	2,240.0	2,240.0	835.8
1981	June	6.54	4.55	1,600.0	800.0	41.1
1981	July	2.53	5.66	629.0	0	10.8
1981	August	3.70	6.03	167.0	0	2.9
1981	September	3.23	4.86	387.0	0	6.6
1981	October	2.08	1.43	321.0	0	5.5
1981	November	.91	1.04	226.0	0	3.9
1981	December	.53	0	96.0	0	1.6
1982	January	1.47	0	0	0	0
1982	February	.46	0	0	0	0
1982	March	1.52	0	63.0	31.5	88.3
1982	April	.22	.45	6,330.0	9,495.0	1,845.4
1982	May	3.13	2.86	12,640.0	12,640.0	4,716.1
1982	June	5.71	4.64	7,960.0	3,980.0	204.6
1982	July	5.91	5.23	5,300.0	0	90.8
1982	August	1.34	5.93	1,350.0	0	23.1
1982	September	1.07	4.79	258.0	0	4.4
1982	October	5.37	1.41	1,890.0	0	32.4
1982	November	.36	1.02	946.0	0	16.2
1982	December	.75	0	661.0	0	11.3

Table B1. Monthly water-balance data for Devils Lake for 1980-99—Continued

[Precipitation, evaporation, and ungaged inflow were estimated using a water-balance model described in this report, and values may not agree with published estimates from earlier studies]

Year	Month	Precipitation (inches)	Evaporation (inches)	Inflow from Big Coulee (acre-feet)	Inflow from Channel A (acre-feet)	Ungaged inflow (acre-feet)
1983	January	1.45	0	760.0	0	13.0
1983	February	.45	0	390.0	0	6.7
1983	March	1.50	0	5,080.0	2,540.0	7,118.7
1983	April	1.08	.45	8,870.0	13,305.0	2,585.9
1983	May	1.51	3.59	7,930.0	7,930.0	2,958.8
1983	June	2.99	5.09	1,960.0	980.0	50.4
1983	July	2.77	5.50	351.0	0	6.0
1983	August	2.10	6.41	21.0	0	.4
1983	September	3.29	5.70	12.0	0	.2
1983	October	1.52	1.68	5.6	0	.1
1983	November	.60	1.21	627.0	483.0	19.0
1983	December	.33	0	355.0	135.0	8.4
1984	January	.75	0	0	2.9	0
1984	February	.40	0	13.0	161.0	3.0
1984	March	1.33	0	105.0	191.0	276.5
1984	April	2.27	1.37	1,940.0	686.0	306.2
1984	May	.34	3.87	1,880.0	473.0	439.0
1984	June	4.14	4.45	1,140.0	2,040.0	54.5
1984	July	1.62	6.06	194.0	16.0	3.6
1984	August	.27	6.67	4.7	7.9	.2
1984	September	1.00	5.34	1.1	413.0	7.1
1984	October	3.43	1.58	7.3	923.0	15.9
1984	November	.90	1.14	16.0	649.0	11.4
1984	December	.83	0	4.0	285.0	5.0
1985	January	.36	0	0	0	0
1985	February	.56	0	0	.3	0
1985	March	1.19	0	407.0	1,050.0	1,361.2
1985	April	.72	1.42	1,430.0	5,600.0	819.8
1985	May	4.91	4.03	1,110.0	296.0	262.3
1985	June	4.00	5.92	559.0	14.0	9.8
1985	July	.43	6.21	133.0	.6	2.3
1985	August	4.89	5.61	40.0	2.6	.7
1985	September	3.79	4.48	12.0	.7	.2
1985	October	4.05	1.32	206.0	237.0	7.6
1985	November	1.59	.95	30.0	532.0	9.6
1985	December	.35	0	1.8	3.7	.1

Table B1. Monthly water-balance data for Devils Lake for 1980-99—Continued

[Precipitation, evaporation, and ungaged inflow were estimated using a water-balance model described in this report, and values may not agree with published estimates from earlier studies]

Year	Month	Precipitation (inches)	Evaporation (inches)	Inflow from Big Coulee (acre-feet)	Inflow from Channel A (acre-feet)	Ungaged inflow (acre-feet)
1986	January	0.33	0	0	0.5	0
1986	February	.57	0	0	0	0
1986	March	.94	0	696.0	684.0	1,289.2
1986	April	3.61	2.68	2,350.0	6,800.0	1,067.0
1986	May	1.86	3.51	4,030.0	6,620.0	1,986.8
1986	June	3.18	7.19	1,620.0	600.0	38.0
1986	July	8.59	4.72	1,740.0	174.0	32.8
1986	August	3.08	6.21	849.0	59.0	15.6
1986	September	3.17	3.76	910.0	32.0	16.2
1986	October	.98	1.11	702.0	1,380.0	35.7
1986	November	3.90	1.74	294.0	2,560.0	48.9
1986	December	.34	0	34.0	661.0	11.9
1987	January	.55	0	10.0	2.1	.2
1987	February	1.85	0	0	0	0
1987	March	.99	0	863.0	133.0	930.5
1987	April	.25	1.31	20,240.0	33,810.0	6,302.9
1987	May	3.26	3.63	15,030.0	21,570.0	6,827.9
1987	June	2.54	7.28	6,640.0	5,970.0	216.1
1987	July	4.80	4.92	3,060.0	93.0	54.0
1987	August	3.73	6.09	1,300.0	22.0	22.7
1987	September	.96	4.32	50.0	24.0	1.3
1987	October	.29	3.82	49.0	1,030.0	18.5
1987	November	.09	1.84	184.0	290.0	8.1
1987	December	.68	0	51.0	3.5	.9
1988	January	1.08	0	.7	.5	0
1988	February	.26	0	2.0	1.2	0
1988	March	1.18	0	73.0	107.0	168.2
1988	April	.06	1.44	611.0	1,220.0	213.5
1988	May	2.00	4.12	123.0	34.0	29.3
1988	June	3.74	8.81	.5	4.1	.1
1988	July	3.09	6.78	.2	0	0
1988	August	1.80	6.63	0	1.2	0
1988	September	.68	4.61	0	.6	0
1988	October	.49	4.08	0	4.6	.1
1988	November	.90	1.97	0	8.5	.2
1988	December	.77	0	0	.5	0

Table B1. Monthly water-balance data for Devils Lake for 1980-99—Continued

[Precipitation, evaporation, and ungaged inflow were estimated using a water-balance model described in this report, and values may not agree with published estimates from earlier studies]

Year	Month	Precipitation (inches)	Evaporation (inches)	Inflow from Big Coulee (acre-feet)	Inflow from Channel A (acre-feet)	Ungaged inflow (acre-feet)
1989	January	1.14	0	0	0	0
1989	February	.16	0	0	0	0
1989	March	1.91	0	3.3	.4	3.5
1989	April	1.65	1.33	222.0	228.0	52.5
1989	May	2.89	3.72	7.2	171.0	33.2
1989	June	3.22	5.08	2.2	1.7	.1
1989	July	1.86	6.90	0	.6	0
1989	August	2.58	6.94	0	.6	0
1989	September	2.31	5.24	0	.6	0
1989	October	.22	4.64	0	.6	0
1989	November	.46	2.24	0	.6	0
1989	December	.15	0	0	.3	0
1990	January	.19	0	0	0	0
1990	February	.50	0	0	0	0
1990	March	2.28	0	0	0	0
1990	April	1.76	1.36	0	19.0	2.2
1990	May	.83	3.81	0	3.0	.6
1990	June	6.14	5.44	0	12.0	.2
1990	July	2.29	5.82	0	7.3	.1
1990	August	2.59	6.76	0	2.2	0
1990	September	1.21	5.89	0	3.8	.1
1990	October	.49	5.21	0	1.4	0
1990	November	.06	2.51	0	.7	0
1990	December	.75	0	0	.6	0
1991	January	.33	0	0	.2	0
1991	February	.78	0	0	0	0
1991	March	.23	0	0	5.4	5.0
1991	April	1.95	1.51	0	5.8	.7
1991	May	3.65	4.39	0	9.6	1.8
1991	June	6.02	4.97	0	5.4	.1
1991	July	6.30	5.87	0	3.5	.1
1991	August	4.28	6.97	0	1.1	0
1991	September	4.71	4.95	0	1.2	0
1991	October	2.77	4.38	0	1.1	0
1991	November	1.03	1.06	0	.6	0
1991	December	.84	0	0	.6	0

Table B1. Monthly water-balance data for Devils Lake for 1980-99—Continued

[Precipitation, evaporation, and ungaged inflow were estimated using a water-balance model described in this report, and values may not agree with published estimates from earlier studies]

Year	Month	Precipitation (inches)	Evaporation (inches)	Inflow from Big Coulee (acre-feet)	Inflow from Channel A (acre-feet)	Ungaged inflow (acre-feet)
1992	January	0.48	0	0	0.6	0
1992	February	.48	0	2.4	4.8	.1
1992	March	1.00	0	1,000.0	538.0	1,436.8
1992	April	1.45	1.37	4,770.0	209.0	580.6
1992	May	1.70	3.86	5,990.0	28.0	1,122.7
1992	June	1.57	5.66	3,720.0	7.4	63.9
1992	July	2.57	3.98	1,590.0	2.7	27.3
1992	August	1.37	5.26	1,250.0	981.0	38.2
1992	September	1.70	4.41	911.0	1,330.0	38.4
1992	October	.07	3.90	402.0	917.0	22.6
1992	November	1.54	.94	123.0	1,170.0	22.2
1992	December	1.10	0	46.0	149.0	3.3
1993	January	.54	0	5.0	1.3	.1
1993	February	.14	0	0	0	0
1993	March	.55	0	68.0	20.0	82.2
1993	April	1.05	1.26	1,450.0	1,250.0	314.8
1993	May	2.36	3.44	1,390.0	6.3	260.5
1993	June	6.06	4.31	1,100.0	1,140.0	38.4
1993	July	12.44	3.43	4,570.0	9,150.0	2,700.2
1993	August	2.47	4.49	16,350.0	76,320.0	18,000.3
1993	September	.20	3.92	19,770.0	40,710.0	12,000.6
1993	October	.33	3.47	15,610.0	11,320.0	5,400.6
1993	November	.32	.84	10,080.0	3,840.0	2,800.6
1993	December	.90	0	5,840.0	1,410.0	1,400.3
1994	January	1.09	0	2,420.0	43.0	42.2
1994	February	.57	0	984.0	11.0	17.0
1994	March	.43	0	3,230.0	2,040.0	4,923.3
1994	April	.22	1.34	21,300.0	33,430.0	6,382.2
1994	May	3.72	3.75	17,560.0	11,050.0	5,337.3
1994	June	9.02	4.55	15,980.0	7,960.0	410.3
1994	July	3.41	4.88	10,500.0	3,230.0	235.3
1994	August	2.55	5.64	5,540.0	159.0	97.7
1994	September	1.98	4.73	1,950.0	145.0	35.9
1994	October	2.86	2.79	2,910.0	11,000.0	238.4
1994	November	2.12	.67	2,230.0	3,960.0	106.1
1994	December	.23	0	3,640.0	281.0	67.2

Table B1. Monthly water-balance data for Devils Lake for 1980-99—Continued

[Precipitation, evaporation, and ungaged inflow were estimated using a water-balance model described in this report, and values may not agree with published estimates from earlier studies]

Year	Month	Precipitation (inches)	Evaporation (inches)	Inflow from Big Coulee (acre-feet)	Inflow from Channel A (acre-feet)	Ungaged inflow (acre-feet)
1995	January	0.35	0	1,770.0	13.0	30.6
1995	February	.42	0	565.0	7.8	9.8
1995	March	1.90	0	8,060.0	7,990.0	14,994.1
1995	April	.77	2.11	68,430.0	70,070.0	16,150.9
1995	May	2.60	4.58	61,080.0	33,980.0	17,733.8
1995	June	2.43	5.16	33,740.0	3,730.0	642.2
1995	July	4.52	6.25	17,470.0	800.0	313.1
1995	August	1.52	6.21	6,530.0	153.0	114.5
1995	September	1.15	5.08	1,570.0	17.0	27.2
1995	October	2.01	2.99	415.0	57.0	8.1
1995	November	1.25	.72	7.2	1,980.0	34.1
1995	December	.95	0	0	35.0	.6
1996	January	.91	0	0	9.4	.2
1996	February	.65	0	0	18.0	.3
1996	March	1.66	0	3.6	16.0	18.3
1996	April	.86	.45	17,730.0	15,200.0	3,840.1
1996	May	1.41	2.70	34,690.0	47,940.0	15,415.0
1996	June	3.55	5.08	19,480.0	16,660.0	619.4
1996	July	4.26	5.02	15,190.0	1,360.0	283.7
1996	August	3.05	6.12	14,730.0	369.0	258.8
1996	September	1.94	4.55	8,410.0	1,500.0	169.8
1996	October	.57	2.69	4,820.0	5,030.0	168.8
1996	November	2.01	.65	2,960.0	4,400.0	126.2
1996	December	1.16	0	1,130.0	7.7	19.5
1997	January	.92	0	68.0	6.1	1.3
1997	February	.19	0	40.0	5.6	.8
1997	March	1.05	0	486.0	63.0	512.9
1997	April	3.11	.45	45,030.0	31,450.0	8,918.5
1997	May	1.17	3.52	122,900.0	83,850.0	38,570.0
1997	June	2.79	7.02	56,700.0	25,300.0	1,405.4
1997	July	6.30	4.75	36,470.0	22,970.0	1,018.8
1997	August	1.44	5.65	21,110.0	11,990.0	567.3
1997	September	1.62	5.02	9,670.0	2,380.0	206.5
1997	October	4.46	2.96	0	5,860.0	100.4
1997	November	.20	.71	0	7,830.0	134.2
1997	December	.31	0	0	2,740.0	47.0

Table B1. Monthly water-balance data for Devils Lake for 1980-99—Continued

[Precipitation, evaporation, and ungaged inflow were estimated using a water-balance model described in this report, and values may not agree with published estimates from earlier studies]

Year	Month	Precipitation (inches)	Evaporation (inches)	Inflow from Big Coulee (acre-feet)	Inflow from Channel A (acre-feet)	Ungaged inflow (acre-feet)
1998	January	0.89	0	0	116.0	2.0
1998	February	2.61	0	0	7.9	.1
1998	March	.33	0	2,744.4	4,460.0	6,730.4
1998	April	1.55	2.08	64,172.5	43,950.0	12,608.4
1998	May	1.70	3.46	34,968.6	17,210.0	9,734.1
1998	June	3.92	4.00	17,829.8	437.0	313.1
1998	July	1.05	5.60	16,213.3	2,510.0	320.9
1998	August	2.19	6.05	6,024.1	601.0	113.6
1998	September	1.53	5.56	675.4	26.0	12.0
1998	October	3.41	3.28	0	973.7	16.7
1998	November	1.00	.79	0	3,753.1	64.3
1998	December	.71	0	0	85.2	1.5
1999	January	.80	0	0	6.1	.1
1999	February	.71	0	0	5.6	.1
1999	March	1.00	0	523.5	495.0	951.5
1999	April	.82	.45	84,226.2	52,320.0	15,923.0
1999	May	2.79	3.14	82,590.6	33,100.0	21,582.6
1999	June	3.19	4.42	39,084.7	715.0	682.2
1999	July	3.77	4.91	20,809.0	6.4	356.8
1999	August	4.58	5.56	17,543.1	6.3	300.8
1999	September	1.91	5.59	16,370.0	6.0	280.7
1999	October	.35	3.30	0	2,000.0	0
1999	November	.04	.79	0	1,000.0	0
1999	December	.48	0	0	0	0

Table B2. Computed surface areas of Devils Lake for 1-foot increments

Lake level (feet above sea level)	Area (acres)					
	West Bay North	West Bay South	Main Bay	East Bay	East Devils Lake	Stump Lake
1,400	0	0	4,567	0	2,818	6,219
1,401	0	0	5,769	0	2,924	6,373
1,402	0	0	6,796	0	3,023	6,520
1,403	0	0	7,708	0	3,116	6,661
1,404	0	0	8,534	0	3,204	6,795
1,405	0	0	9,292	0	3,286	6,925
1,406	0	0	9,995	1,670	3,363	7,050
1,407	0	0	10,651	2,845	3,436	7,172
1,408	0	0	11,267	3,884	3,505	7,290
1,409	0	0	11,848	4,842	3,569	7,406
1,410	0	0	12,398	5,744	3,630	7,520
1,411	0	0	12,920	6,604	3,688	7,633
1,412	0	0	13,417	7,429	3,743	7,745
1,413	0	0	13,890	8,225	3,795	7,857
1,414	0	0	14,342	8,996	3,845	7,970
1,415	0	0	14,775	9,747	3,892	8,084
1,416	0	302	15,190	10,478	3,938	8,200
1,417	0	849	15,589	11,191	3,983	8,320
1,418	0	1,626	15,972	11,889	4,026	8,442
1,419	0	2,625	16,342	12,572	4,068	8,568
1,420	0	3,820	16,698	13,242	4,110	8,699
1,421	0	5,173	17,042	13,900	4,152	8,835
1,422	0	6,633	17,376	14,545	4,194	8,978
1,423	0	8,153	17,701	15,179	4,237	9,126
1,424	0	9,685	18,017	15,802	4,281	9,282
1,425	0	11,192	18,326	16,415	4,326	9,446
1,426	0	12,646	18,628	17,018	4,374	9,619
1,427	0	14,029	18,926	17,611	4,423	9,800
1,428	0	15,332	19,220	18,195	4,476	9,992
1,429	0	16,550	19,511	18,770	4,531	10,194
1,430	0	17,688	19,802	19,337	4,590	10,406
1,431	341	18,750	20,092	19,895	4,654	10,630
1,432	838	19,744	20,385	20,444	4,721	10,866
1,433	1,277	20,678	20,680	20,987	4,794	11,115
1,434	1,706	21,559	20,981	21,522	4,872	11,377

Table B2. Computed surface areas of Devils Lake for 1-foot increments—Continued

Lake level (feet above sea level)	Area (acres)					
	West Bay North	West Bay South	Main Bay	East Bay	East Devils Lake	Stump Lake
1,435	2,233	22,396	21,288	22,050	4,956	11,653
1,436	2,955	23,196	21,603	22,571	5,047	11,942
1,437	3,946	23,965	21,927	23,088	5,144	12,246
1,438	5,261	24,708	22,262	23,599	5,248	12,566
1,439	6,943	25,431	22,611	24,106	5,360	12,900
1,440	9,027	26,136	22,973	24,611	5,480	13,250
1,441	11,538	26,827	23,352	25,115	5,608	13,616
1,442	14,492	27,506	23,748	25,618	5,745	13,998
1,443	17,904	28,176	24,162	26,124	5,890	14,397
1,444	21,779	28,837	24,596	26,633	6,044	14,812
1,445	26,123	29,491	25,050	27,148	6,207	15,244
1,446	30,936	30,138	25,527	27,671	6,380	15,692
1,447	36,219	30,779	26,025	28,204	6,561	16,158
1,448	41,973	31,413	26,546	28,749	6,752	16,640
1,449	48,198	32,040	27,089	29,309	6,952	17,139
1,450	54,894	32,661	27,654	29,885	7,161	17,654
1,451	62,065	33,274	28,241	30,479	7,378	18,186
1,452	69,715	33,879	28,849	31,091	7,604	18,734
1,453	77,849	34,474	29,477	31,721	7,839	19,297
1,454	86,477	35,059	30,123	32,369	8,080	19,876
1,455	95,609	35,631	30,785	33,034	8,330	20,470
1,456	105,262	36,190	31,462	33,712	8,585	21,078
1,457	115,454	36,734	32,151	34,402	8,847	21,701
1,458	126,211	37,261	32,851	35,099	9,114	22,336
1,459	137,563	37,768	33,557	35,800	9,386	22,984
1,460	149,550	38,254	34,268	36,501	9,662	23,643

Table B3. Computed volumes of Devils Lake for 1-foot increments

Lake level (feet above sea level)	Volume (acre-feet)					
	West Bay North	West Bay South	Main Bay	East Bay	East Devils Lake	Stump Lake
1,400	0	0	5,770	0	23,333	76,705
1,401	0	0	10,957	0	26,204	83,002
1,402	0	0	17,251	0	29,178	89,449
1,403	0	0	24,511	0	32,248	96,040
1,404	0	0	32,638	0	35,408	102,768
1,405	0	0	41,556	0	38,653	109,629
1,406	0	0	51,204	944	41,978	116,617
1,407	0	0	61,530	3,217	45,378	123,728
1,408	0	0	72,493	6,589	48,849	130,960
1,409	0	0	84,053	10,957	52,386	138,308
1,410	0	0	96,179	16,254	55,986	145,771
1,411	0	0	108,840	22,432	59,646	153,347
1,412	0	0	122,011	29,450	63,362	161,036
1,413	0	0	135,666	37,279	67,131	168,836
1,414	0	0	149,784	45,892	70,952	176,750
1,415	0	0	164,345	55,265	74,820	184,777
1,416	0	127	179,329	65,379	78,736	192,919
1,417	0	684	194,720	76,215	82,697	201,178
1,418	0	1,902	210,502	87,756	86,701	209,559
1,419	0	4,010	226,660	99,988	90,748	218,063
1,420	0	7,218	243,180	112,897	94,838	226,696
1,421	0	11,704	260,052	126,469	98,969	235,463
1,422	0	17,600	277,262	140,692	103,142	244,369
1,423	0	24,990	294,801	155,555	107,358	253,421
1,424	0	33,909	312,661	171,046	111,617	262,624
1,425	0	44,351	330,833	187,156	115,921	271,988
1,426	0	56,276	349,310	203,873	120,271	281,520
1,427	0	69,620	368,088	221,189	124,669	291,229
1,428	0	84,307	387,161	239,093	129,119	301,124
1,429	0	100,255	406,526	257,576	133,622	311,216
1,430	0	117,381	426,183	276,631	138,182	321,515
1,431	134	135,607	446,130	296,247	142,804	332,032
1,432	726	154,859	466,368	316,417	147,490	342,779
1,433	1,788	175,075	486,900	337,133	152,248	353,769
1,434	3,276	196,197	507,731	358,388	157,080	365,014

Table B3. Computed volumes of Devils Lake for 1-foot increments—Continued

Lake level (feet above sea level)	Volume (acre-feet) West Bay North	West Bay South	Main Bay	East Bay	East Devils Lake	Stump Lake
1,435	5,233	218,178	528,864	380,174	161,994	376,528
1,436	7,808	240,976	550,309	402,485	166,995	388,324
1,437	11,233	264,559	572,073	425,315	172,090	400,417
1,438	15,808	288,897	594,166	448,658	177,286	412,822
1,439	21,878	313,968	616,602	472,511	182,589	425,554
1,440	29,828	339,753	639,393	496,870	188,009	438,627
1,441	40,074	366,235	662,554	521,733	193,552	452,059
1,442	53,052	393,402	686,102	547,100	199,228	465,864
1,443	69,212	421,244	710,055	572,971	205,044	480,060
1,444	89,014	449,751	734,432	599,349	211,011	494,663
1,445	112,926	478,916	759,254	626,238	217,136	509,689
1,446	141,416	508,731	784,541	653,647	223,428	525,156
1,447	174,955	539,190	810,314	681,583	229,898	541,079
1,448	214,012	570,286	836,598	710,059	236,554	557,477
1,449	259,058	602,013	863,413	739,086	243,405	574,364
1,450	310,564	634,365	890,783	768,682	250,461	591,760
1,451	369,005	667,333	918,729	798,863	257,730	609,678
1,452	434,855	700,910	947,272	829,646	265,220	628,137
1,453	508,596	735,088	976,433	861,050	272,941	647,151
1,454	590,717	769,855	1,006,232	893,094	280,900	666,737
1,455	681,718	805,201	1,036,684	925,794	289,105	686,909
1,456	782,109	841,113	1,067,806	959,166	297,562	707,682
1,457	892,420	877,577	1,099,612	993,222	306,277	729,071
1,458	1,013,205	914,576	1,132,113	1,027,972	315,258	751,088
1,459	1,145,040	952,093	1,165,316	1,063,422	324,507	773,747
1,460	1,288,543	990,106	1,199,229	1,099,573	334,031	797,059

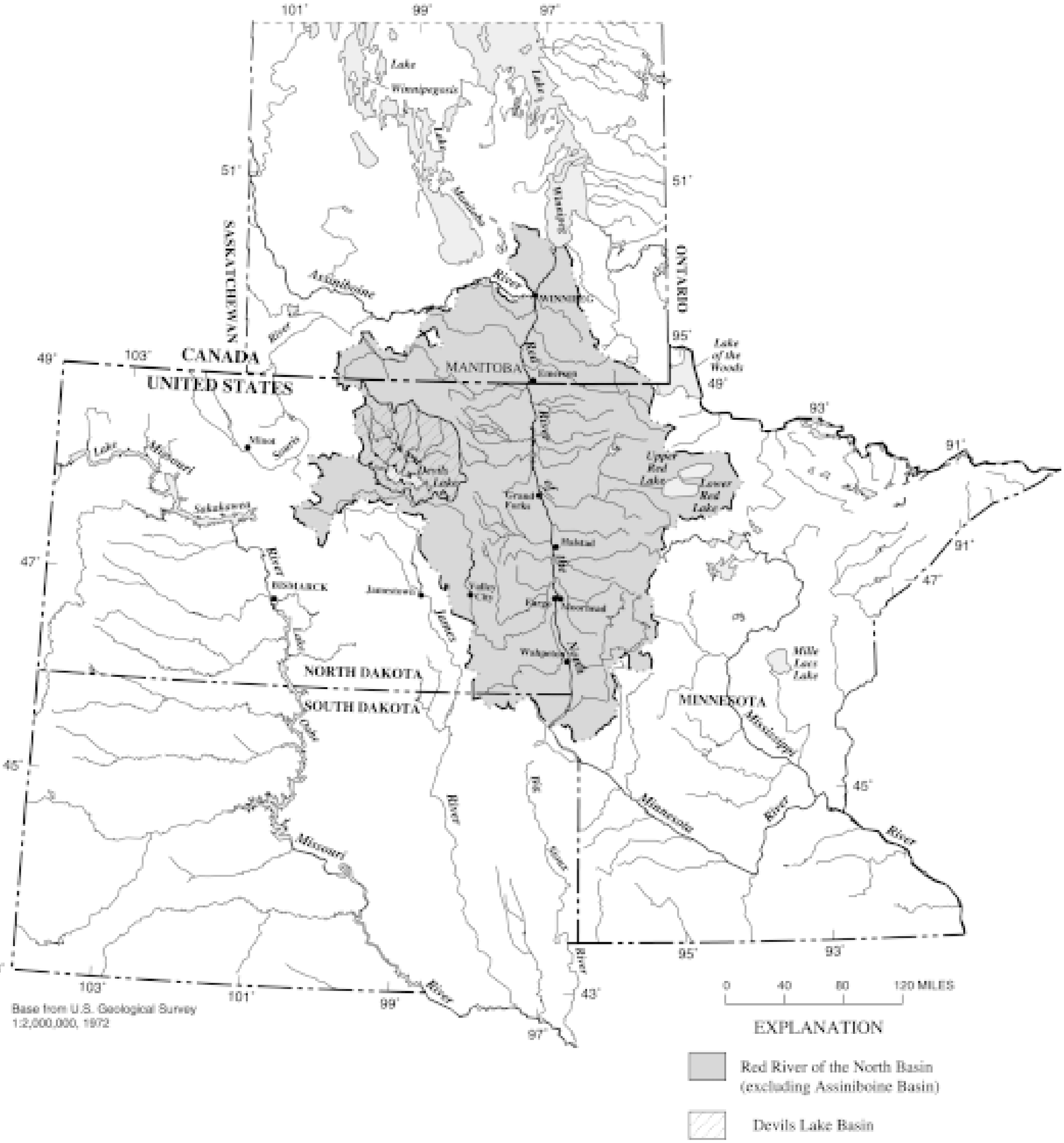

Figure 1. Locations of the Devils Lake Basin and the Red River of the North Basin.

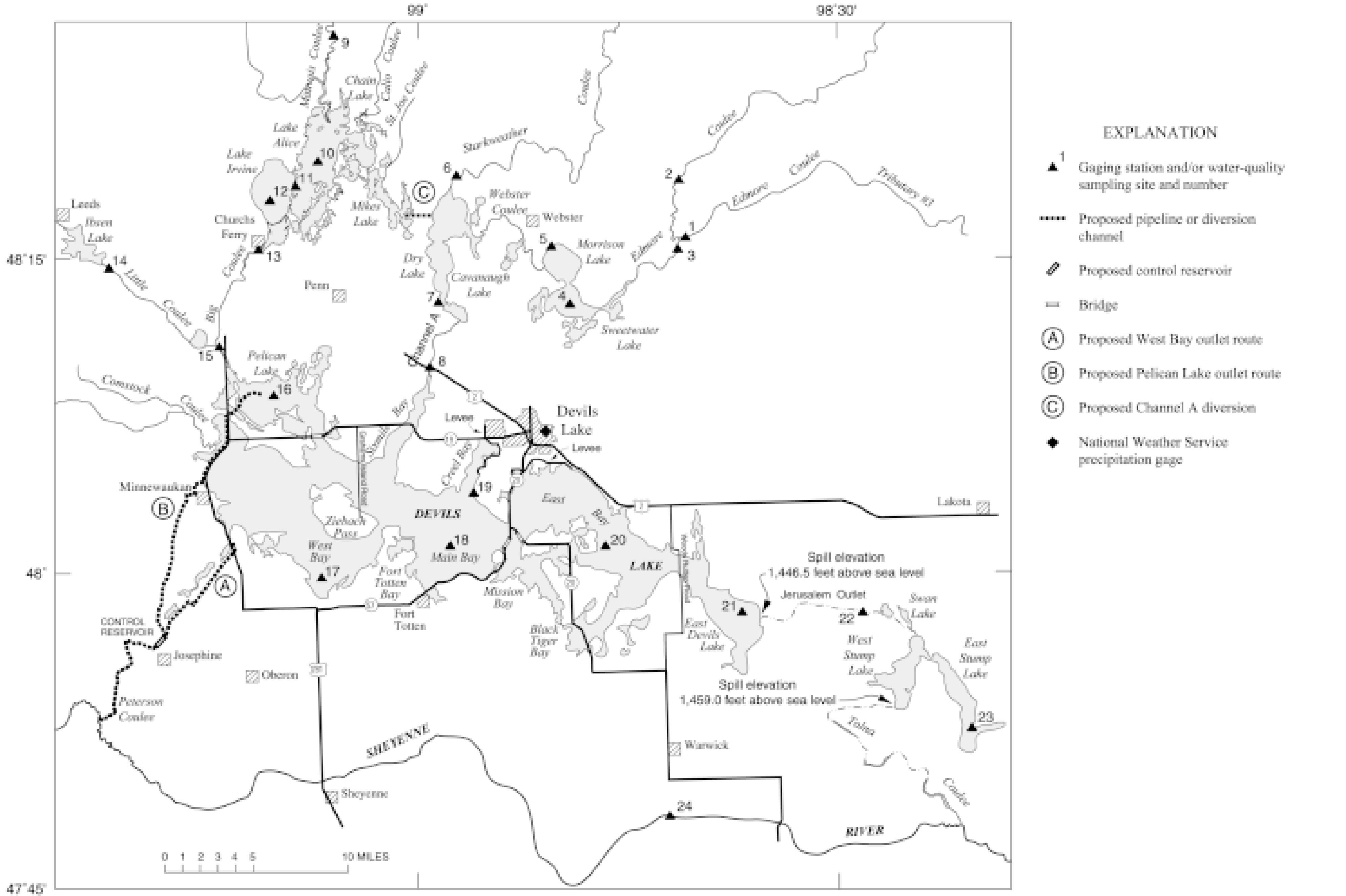

Figure 2. Locations of gaging stations and water-quality sampling sites in the Devils Lake Basin and proposed outlet routes for West Bay and Pelican Lake. (Level of Devils Lake is 1,445 feet above sea level.)

Figure 3. Recorded lake level for Devils Lake, 1867-2001.

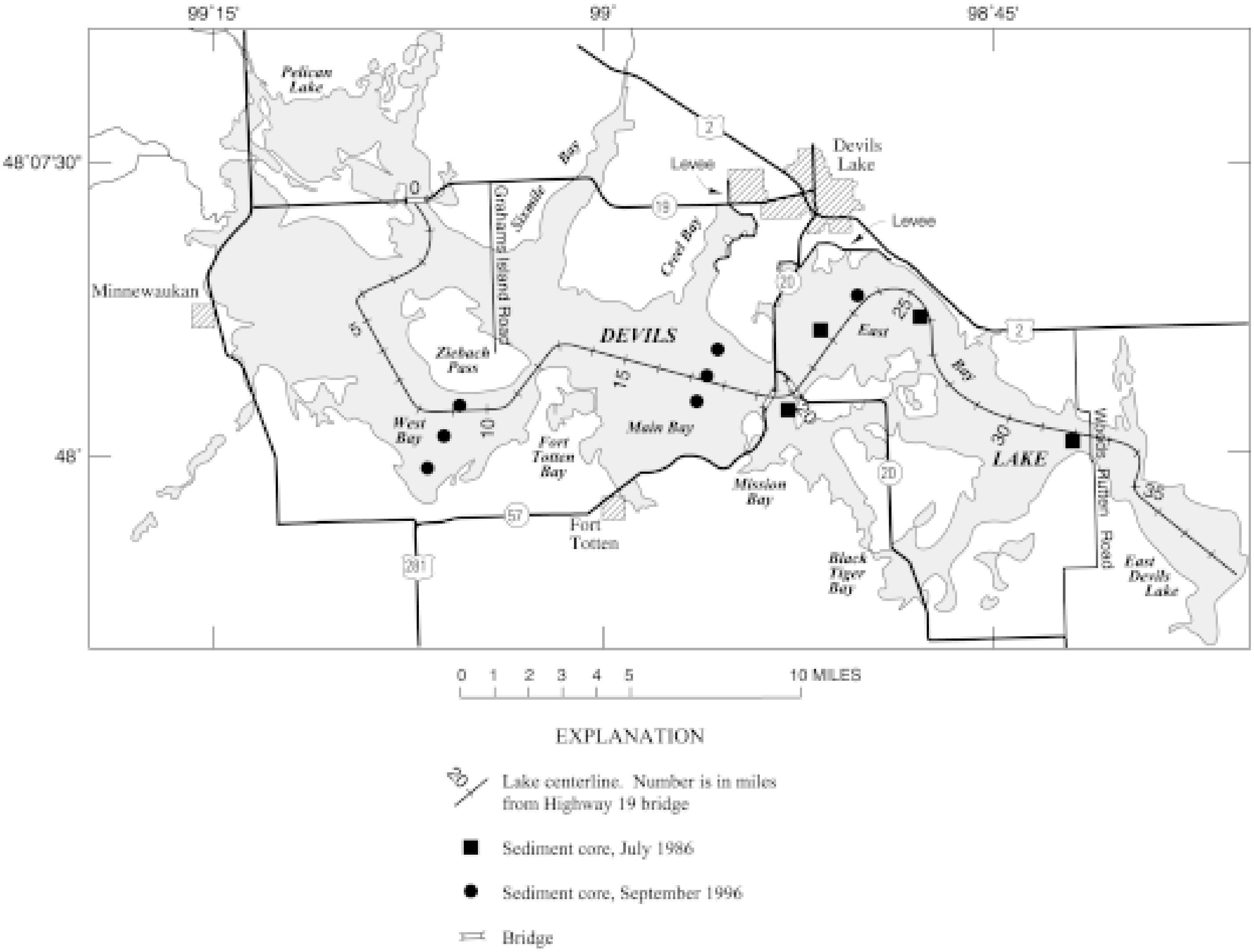

Figure 24. Locations of sediment cores taken from Devils Lake in July 1986 and September 1996.